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# SECONDARY POWER SYSTEM STUDY FOR ADVANCED ROTARY-WING AIRCRAFT

By

John Karpis
Louis J. Levine
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November 1971

## EUSTIS DIRECTORATE
## U. S. ARMY AIR MOBILITY RESEARCH AND DEVELOPMENT LABORATORY
## FORT EUSTIS, VIRGINIA

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THE BOEING COMPANY, VERTOL DIVISION

PHILADELPHIA, PENNSYLVANIA

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13. ABSTRACT

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Pertinent characteristics for main engines, APU's, and SPS components applicable to the study were determined from surveys of manufacturers, and projected APU design characteristics in the small size class anticipated for the SPS were derived from a parametric APU cycle study. System functions and loads were established, and candidate systems were synthesized for preliminary evaluation and design. The cockpit environmental control system and main-engine starting with an inoperable APU were exercised as optional functions of the SPS. Comparative weight, life-cycle cost, reliability, maintainability, and performance parameters were assessed to select optimum systems for each level of technology.

This report also documents the recommended research and development to accomplish advances in SPS component technologies which will contribute to significant improvements in system characteristics - performance, weight and/or volume, and mechanical integrity.

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| Secondary Power System | | | | | | |
| Helicopter Secondary Power | | | | | | |
| Auxiliary Power Unit | | | | | | |

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DEPARTMENT OF THE ARMY
U. S. ARMY AIR MOBILITY RESEARCH & DEVELOPMENT LABORATORY
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FORT EUSTIS, VIRGINIA 23604

The study described herein was conducted by the Boeing Company, Vertol Division under the terms of Contract DAAJ02-70-C-0046. The work was performed under the technical management of Mr. Paul Chesser, Propulsion Division, Eustis Directorate, U.S. Army Air Mobility Research and Development Laboratory.

The object of this study effort was to determine three optimum secondary power systems (SPS) for advanced rotary-wing aircraft, using three levels of technology, and to recommend the research and development required to achieve technological advancements in SPS components which could provide significant improvements for future aircraft.

Appropriate technical personnel of this Directorate have reviewed this report and concur with the findings contained herein.

Costing and required program levels described are the views of the contractor and are not necessarily the views of the Eustis Directorate, USAAMRDL. Therefore, caution is recommended in the use of those data.

This report is recommended for use in planning secondary power systems for future Army rotary-wing aircraft.

Task 1G162203D14415
Contract DAAJ02-70-C-0046
USAAMRDL Technical Report 71-52
November 1971

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Final Report

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Prepared by

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for

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U.S. ARMY AIR MOBILITY RESEARCH AND DEVELOPMENT LABORATORY
FORT EUSTIS, VIRGINIA

## ABSTRACT

Future Army aircraft will be required to operate in areas where it is impractical to provide ground support equipment to supply various types of power for systems check-out, standby, and main-engine starting. An auxiliary power unit (APU) with accessories in the aircraft will be necessary to furnish secondary power on the ground or in flight. This report describes the results of a study to determine three optimum secondary power systems (SPS) for advanced rotary-wing aircraft, utilizing three different levels of technology, and to recommend research and development required to achieve technological advancements in SPS components which can provide significant improvements for future aircraft. The secondary power system is a subsystem of the aircraft consisting of the power producing components, which include the APU, APU starting system, accessory gearbox and driven accessories (hydraulic pumps, electrical generators, etc.), cabin heating and ventilation, and avionics cooling, plus the power distribution system to interconnect these components.

Pertinent characteristics for main engines, APU's, and SPS components applicable to the study were determined from surveys of manufacturers, and projected APU design characteristics in the small size class anticipated for the SPS were derived from a parametric APU cycle study. System functions and loads were established, and candidate systems were synthesized for preliminary evaluation and design. The cockpit environmental control system and main-engine starting with an inoperable APU were exercised as optional functions of the SPS. Comparative weight, life-cycle cost, reliability, maintainability, and performance parameters were assessed to select optimum systems for each level of technology.

The optimum SPS (lightest, most reliable, lowest cost) had a single-shaft APU mounted on and driving directly into the accessory gearbox, providing bleed air and shaft horsepower. An air-cycle machine for environmental control, an air turbine starter (ATS) on each main engine, and the necessary pneumatic plumbing were included. The APU was started from a hydraulic accumulator. SPS operation would be independent of main-engine and rotor operation for check-out.

This report also documents the recommended research and development to accomplish advances in SPS component technologies which will contribute to significant improvements in system characteristics - performance, weight and/or volume, and mechanical integrity. In particular, design, development, and qualification of an auxiliary power unit and an air turbine starter applicable to the helicopter requirement are recommended.

# FOREWORD

This report completes the engineering study to define and evaluate secondary power systems applicable to future Army aircraft authorized by Contract DAAJ02-70-C-0046, DA Task 1G162203D14415, Secondary Power System for Advanced Rotary-Wing Aircraft.

The authors acknowledge the assistance of the companies listed below, who were most cooperative in responding to the survey of main engine manufacturers and SPS component manufacturers (auxiliary power units and hydraulic, pneumatic, electrical, environmental control system components), and in participating in follow-up interviews:

Abex Corporation, Aerospace Division, Oxnard, California
AiResearch Manufacturing Division, The Garrett Corporation, Phoenix, Arizona, and Los Angeles, California
AVCO Lycoming Division, Stratford, Connecticut
Bendix, Electric Power Division, Eatontown, New Jersey
Chandler Evans, Inc., West Hartford, Connecticut
Chatham Electronic Division, Livingston, New Jersey
Detroit Diesel Allison Division, Indianapolis, Indiana
General Electric Company, West Lynn, Massachusetts
Hamilton-Standard Division, United Aircraft Corporation, Windsor Locks, Connecticut
Hartman Electrical, Mansfield, Ohio
Lear-Siegler, Inc., Cleveland, Ohio
Mechanical Productions, Jackson, Michigan
Pratt & Whitney Aircraft Division, United Aircraft Corporation, West Palm Beach, Florida
Solar Division, International Harvester Company, San Diego, California
Sundstrand Aviation/Sundstrand Avionics Divisions, Rockford, Illinois
Teledyne CAE, Toledo, Ohio
United Aircraft of Canada, Ltd., Montreal, Canada
Vickers, Inc., Division of Sperry Rand Corporation, Troy, Michigan

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## LIST OF SYMBOLS

| | |
|---|---|
| A | axial compressor, turbine stages in APU |
| AHP | air horsepower - power available by ideal expansion from total temperature and pressure to ambient pressure, hp |
| C | centrifugal compressor stage in APU |
| $C_{bl}$ | air bleed correction factor for main-engine fuel flow |
| $C''_{bl}$ | air bleed correction factor for main-engine shaft horsepower |
| CPR | compressor total pressure ratio, exit-to-inlet |
| D | diameter, in. |
| d | hydraulic motor displacement = $\frac{24\pi\tau}{P}$ (Appendix III), in.$^3$/rev |
| ESFC | equivalent specific fuel consumption of APU - fuel flow divided by equivalent shaft horsepower, lb/hr/eshp |
| ESHP | equivalent shaft horsepower of APU - actual shaft power plus air horsepower, hp |
| H | height of APU, in. |
| HP | horsepower (fluid coupling, Appendix III), hp |
| I | polar moment of inertia, slug-ft$^2$ |
| L | length of APU, in. |
| N | shaft speed, rpm |
| $N_2$ | APU output shaft speed, rpm |
| p | pressure, psia |
| $P_{bl}$ | bleed air pressure at bleed port, psia |
| $P_i$ | initial hydraulic pressure, psig |

| | |
|---|---|
| R | radial turbine stage in APU |
| SFC | engine specific fuel consumption - fuel flow divided by shaft horsepower, lb/hr/hp |
| SHP | engine shaft horsepower, hp |
| T | temperature, °F/°R |
| $T_{bl}$ | bleed air temperature at bleed port, °F/°R |
| TIT | turbine-inlet temperature, °F/°R |
| t | time, sec |
| $V_i$ | initial gas volume (Appendix III, IV), $in.^3$ |
| W | width of APU, in. |
| $W_a$ | engine inlet airflow, lb/sec |
| $W_f$ | engine fuel flow, lb/hr |
| $W_{IN}$ | inlet flow for bleed APU (Appendix I), lb/sec |
| $\Delta$ | increment or change in parameter |
| $\Delta h_{bl}$ | compressor work per pound of air to bleed-port pressure pressure, Btu/lb |
| $\Delta W_{bl}$ | compressor bleed airflow, lb/sec |
| $\delta$ | ambient pressure divided by NASA standard day pressure, $P_{am}/14.696$ psia |
| $\eta_{GEAR}$ | shaft output gearbox efficiency |
| $\eta_m$ | mechanical efficiency of compressor shaft (losses in bearings, disk friction and windage, etc.) |
| $\theta$ | ambient temperature (°R) divided by NASA standard day temperature, $T_{am}/518.7$ |
| $\tau$ | torque at starter pad, lb-ft |
| $\mu$ | viscosity of oil, centistokes |

## SUBSCRIPTS

| | |
|---|---|
| am | ambient air |
| av | average |
| bl | bleed airflow properties |
| e | engine |
| ID | inside diameter, in. |
| i | initial (starter conditions - Appendix IV) |
| OD | outside diameter, in. |
| s | starter |
| 2 | end of interval $\Delta N$ or $\Delta t$ |

## SUPERSCRIPTS

| | |
|---|---|
| * | conditions at Military (30-minute) Power Setting, sea level static, standard day ambient atmosphere |

## SUMMARY

Future Army rotary-wing aircraft will be required to operate in areas where it is impractical to provide ground support equipment to supply various types of power for systems check-out, standby, and main-engine starting. An auxiliary power unit (APU) with accessories in the aircraft will be necessary to supply secondary power when the aircraft is on the ground or in flight. The secondary power system (SPS) is a subsystem of the helicopter and consists of the power-producing components, which include the APU, APU starting system, accessory gearbox and driven accessories (hydraulic pumps, electrical generators, etc.), main-engine starting, cabin heating and ventilation, and avionics cooling, plus the power distribution system to interconnect these components. The SPS must enable the helicopter to be self-supporting at remote sites, while providing inherent high dispatch reliability and complete ground check-out and emergency power capability, consistent with mission requirements.

Eustis Directorate, U.S. Army Air Mobility Research and Development Laboratory, contracted with The Boeing Company, Vertol Division, to conduct an engineering study to define existing and advanced secondary power system technology applicable to future rotary-wing aircraft. The design requirements for the Army's Utility Tactical Transport Aircraft System (UTTAS) - pictured in Figure 1 - were the basis of the study. Boeing determined the optimum integrated secondary power system for the 1970 baseline UTTAS, using each of three levels of SPS technology as follows:

1. A secondary power system that utilizes existing technology.

2. A secondary power system that utilizes advanced technology compatible with a 1975 production time period.

3. A secondary power system that utilizes advanced technology compatible with a 1985 production time period.

In formulating the Secondary Power System, it was necessary to establish all the vehicle functions requiring secondary power service, and maximum component commonality was provided in performing these functions. In particular, the baseline aircraft design required hydraulic, electric, and pneumatic secondary power. Flight controls, landing gear retraction, the utility system, and the cargo hook system required hydraulic power. Instruments, avionics, armament, de-icing,

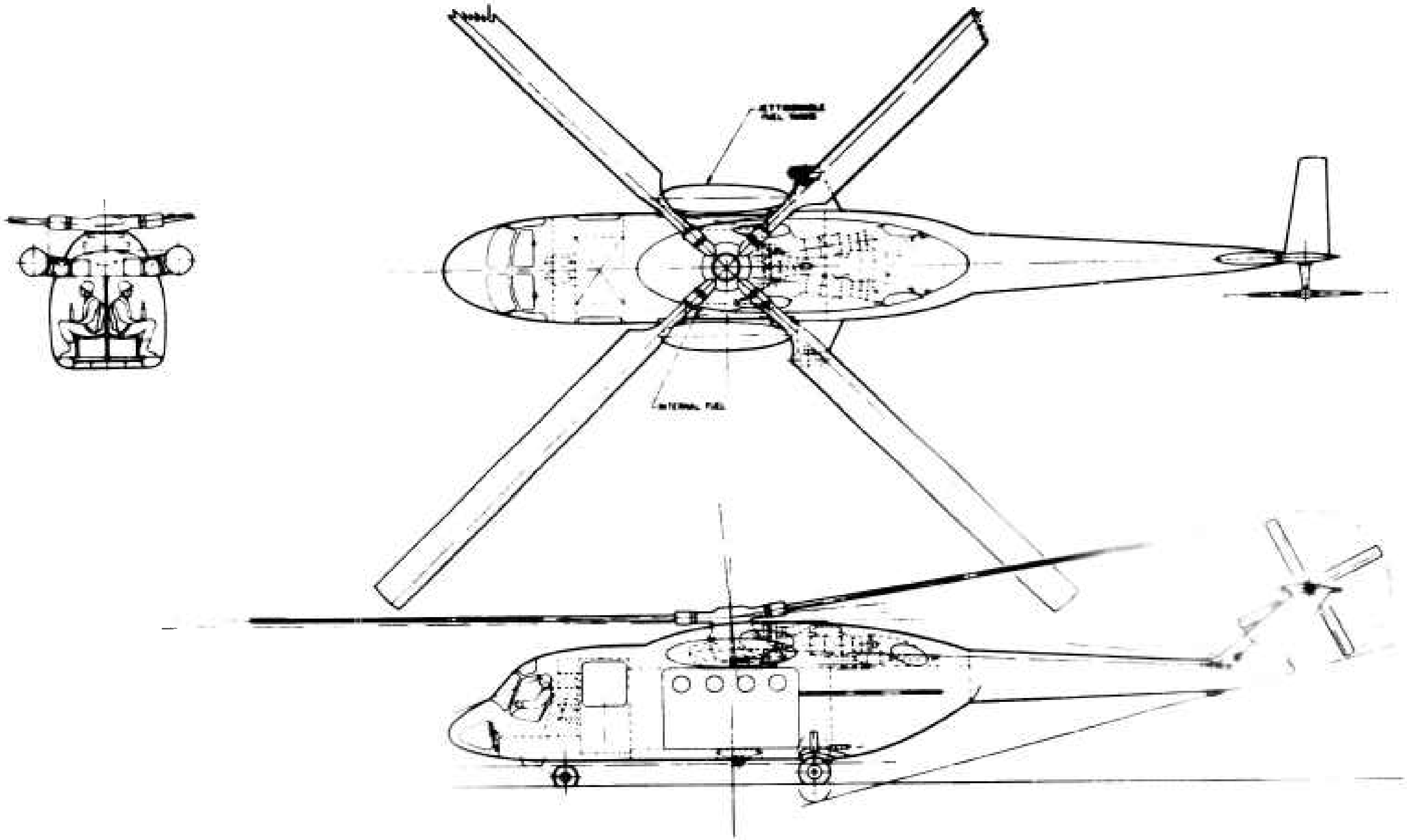


Figure 1. Baseline Helicopter Design for SPS Study.

electronic countermeasures, lights, and the litter hoist required electric power. A pneumatic system was required for environmental conditioning of equipment, and possibly the crew. Starting the main engines and the APU were required functions, and all the various methods were considered - hydraulic, electric, and pneumatic. The study also included ground check-out for maintenance, independent of main-engine operation. The cockpit (crew) environmental control system and main-engine starting with an inoperable APU were exercised as optional functions of the SPS.

Engine manufacturers were surveyed to establish the starting torque requirements for the main engines and their bleed capability, identifying bleed-air quality and impact on engine performance (for possible inflight air supply to the environmental control system and to re-start the main engines). A 20-hp starter capability met or exceeded starting torque requirements for all the main engine candidates. Major manufacturers of auxiliary power units and SPS components also were solicited to provide size, weight, efficiency, and other pertinent parameters for their products, with technological trends and anticipated innovations for components of the desired levels of technology. The results of the APU and SPS component surveys were correlated, to provide the basis for recommending criteria to be used during the remainder of the study.

A parametric APU cycle study was conducted to determine comparative design-point performance for nonregenerative and regenerative engines. Consistent values of pressure losses, component efficiencies, parasitic airflows, and accessory powers, obtained from analyses of selected engines covered in the APU survey, were used to generate overall performance consistent with the survey engine trends. Aircraft secondary power requirements dictated a small APU, and the parametric engine performance characteristics reflected the anticipated small size. Selection of APU characteristics applicable to each level of technology were based on the results of this parametric study. APU performance, weight, and design data for various secondary power system configurations are listed in Table I.

Design of the secondary power system was based upon definition of the types of power required and of the various system interfaces, and consideration of all the possible methods and concepts to perform system functions. Power requirements and operational sequences were analyzed for each function, and the SPS was planned to provide power for all ground and flight requirements. Power sharing, which accounted for each function requiring secondary power service and its scheduled use, minimized SPS power demand and consequently system size and weight. Power requirements for various SPS configurations - shaft power and bleed air - are also listed in Table I.

TABLE I. APU PERFORMANCE AND WEIGHT CHARACTERISTICS FOR DIFFERENT SPS CONFIGURATIONS

| Ambient Conditions | Sea Level, 130°F APU Design Point | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| APU Requirements<br>Bleed, Lb/Min<br>SHP | 20<br>26 | | | 20<br>17 | | | 36<br>- | | | 20<br>17 | 20<br>17 |
| Type of APU | Single Shaft Integral Bleed | | | Single Shaft Integral Bleed | | | Single Shaft Integral Bleed | | | Single Shaft Torque Converter Integral Bleed | Free Turbine Integral Bleed |
| Technology Level | 1970 | 1975 | 1985 | 1970 | 1975 | 1985 | 1970 | 1975 | 1985 | 1970 | 1970 |
| Compressor Pressure Ratio | 4:1 | 6:1 | 8:1 | 4:1 | 6:1 | 8:1 | 4:1 | 6:1 | 8:1 | 4:1 | 4:1 |
| Turbine-Inlet Temperature, °F | 1800 | 2000 | 2250 | 1800 | 2000 | 2250 | 1800 | 2000 | 2250 | 1800 | 1800 |
| APU Inlet Airflow, Lb/Sec | 1.68 | 1.16 | 0.94 | 1.52 | 1.05 | 0.86 | 2.14 | 1.50 | 1.24 | 1.52 | 1.52 |
| Bleed Fraction of Inlet Airflow | .198 | .288 | .354 | .219 | .317 | .387 | .273 | .389 | .470 | .219 | .219 |
| Bleed Pressure Ratio | 4:1 | 4:1 | 4:1 | 4:1 | 4:1 | 4:1 | 4:1 | 4:1 | 4:1 | 4:1 | 4:1 |
| Equivalent SHP at 130°F, HP | 76. | 74. | 71. | 66. | 64. | 62. | 86. | 82. | 78. | 66. | 66. |
| APU Weight, Lb | 100. | 58. | 36. | 87. | 50. | 32. | 94. | 57. | 37. | 91. | 113. |

Table II lists SPS functional elements from which systems could be synthesized. Several concepts were evaluated for each function - some being eliminated from further consideration after perfunctory analyses and others after detailed comparative evaluations. One example of the tradeoff studies performed was the comparison of a shaft-power APU powering an engine-driven compressor and accessories with an integral-bleed shaft power machine. In this instance, the bleed APU was the lightest configuration and did not compromise the accessory gearbox. The preliminary evaluations reduced the number of candidate functional elements to the items in Table II which are boxed in, and these remaining candidates were subjected to an in-depth analysis for system comparisons in succeeding program tasks.

The system selected as the optimum SPS, illustrated in Figure 2, has a single-shaft APU mounted on and driving directly into the accessory gearbox (AGB), to provide bleed air and shaft horsepower. Also included in the system are an air-cycle machine for environmental control, an air turbine starter mounted on each main engine, and the necessary pneumatic plumbing. The APU is started from a hydraulic accumulator and simultaneously provides the bleed airflow for engine starting, and electrical and hydraulic power generation for the ancillary services required during the engine starting cycle. The APU is pictured in Figure 3.

The principal reasons for selecting the functional elements of the SPS configuration are listed below:

1. An ATS was selected for main-engine starting because it offered the advantages of low weight, small size, and high dispatch reliability; it used a nonflammable power transfer medium; and inflight re-starts could be achieved by bleed from the operating engine.

2. Hydraulic APU starting provided all-weather capability with unlimited multi-start capacity.

3. Hydraulic and electric components driven by the AGB was the simplest arrangement for the main transmission and the APU drive.

4. The single-shaft APU was the least costly and most reliable of the candidates, and the weight penalty due to driving the AGB during APU starting was slight.

5. The selection of an air-cycle machine for environmental control was based on superior reliability and minimum weight.

TABLE II. FUNCTIONAL ELEMENTS TO SYNTHESIZE SECONDARY POWER SYSTEMS

| SPS Functions | Candidate Functional Elements |
|---|---|
| Main-Engine Start | Hydraulic Motor<br>Hydraulic Motor-Pump<br>Air Turbine Starter<br>Electric Motor<br>Starter-Generator<br>Mechanical Link to Accessory Gearbox (AGB) |
| Transmission Accessory Drive | Direct Gear Coupling<br>Hydraulic-Driven AGB<br>Pneumatic-Driven AGB<br>Shaft-Driven AGB |
| Auxiliary Power Unit | Single Shaft, Integral Bleed<br>Free Turbine, Integral Bleed<br>Single Shaft, No Bleed<br>Free Turbine, No Bleed |
| APU Start | DC Motor<br>Starter-Generator<br>Hydraulic Motor<br>Hydraulic Motor-Pump<br>ATM |
| Electrical Power Generation | AC Generator System<br>DC Generator System |
| Generator Drive | Transmission<br>Hydraulic Motor<br>ATM |
| Flight Hydraulic Power Generation | Transmission-Driven Pumps<br>Pneumatic-Driven Pumps<br>Electric Motor-Driven Pumps<br>Engine-Driven Pumps |
| Pneumatic Power Generation | Engine Bleed<br>Transmission-Driven Compressor |
| Air Conditioning | Air Cycle<br>Vapor Cycle |
| Heating/Ventilation | Bleed-Air Heater<br>Combustor Heater<br>Electric Heater |
| Main-Engine Start With Inoperable APU | Cartridge Hydraulic, Pneumatic Starter<br>Cartridge Power, Impingement Starter<br>Cartridge Power to Drive APU<br>Accumulator<br>Buddy System |
| Emergency SPS | Transmission Driven Generator, Pump<br>Battery and Inverter<br>Hydrazine-Driven Generator and Pump<br>APU |

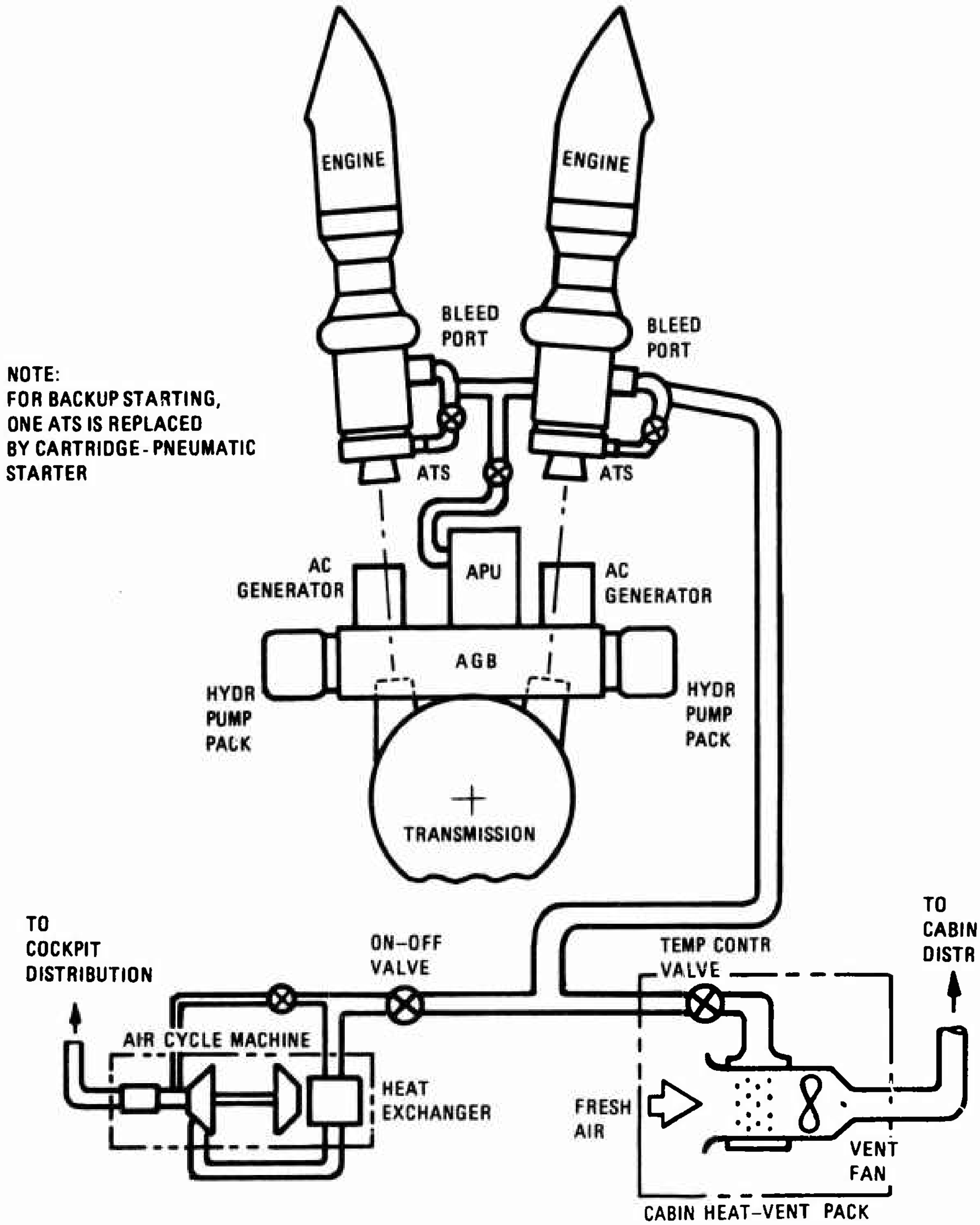



Figure 2. Optimum Secondary Power System for Utility Tactical Helicopter.

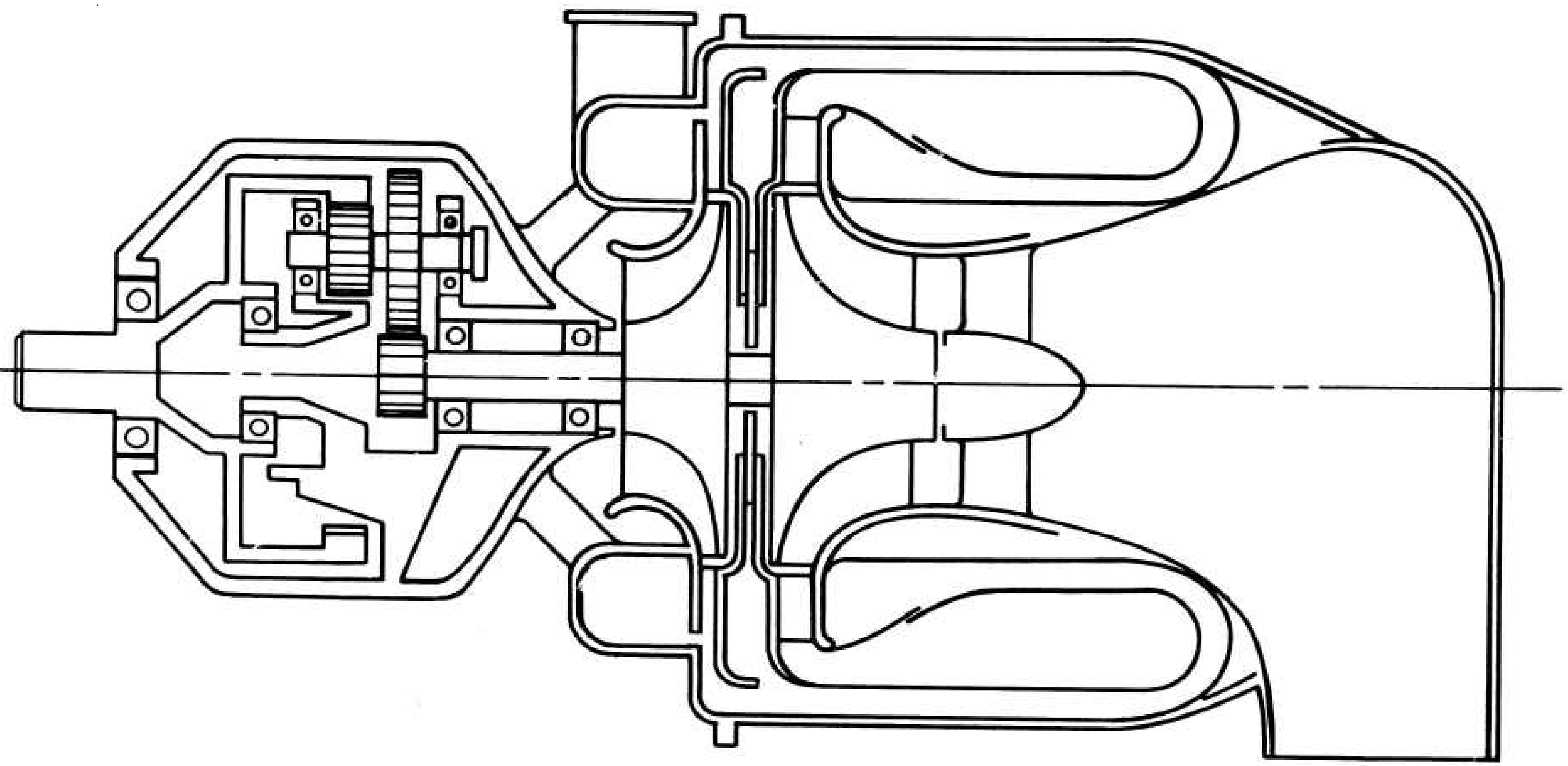


Figure 3. Single-Shaft APU for Bleed and Shaft Power.

6. The cartridge pneumatic starter for backup main-engine starting was the lightest, least costly component and simplest to incorporate in the SPS.

A cartridge pneumatic starter for main-engine starting with an inoperable APU, replacing the ATS, would increase the SPS weight from 465 to 490 pounds and would increase the life-cycle system cost by 4 percent, which includes a very small impact on SPS maintainability. However, the backup starting provision would improve the dispatch availability of the aircraft substantially. Failures per 1000 hours would be reduced from 8.4 to less than 1.1. Cockpit cooling with the ECS system would increase SPS weight from 465 to 497 pounds and would increase life-cycle system cost by 8 percent.

The SPS program uncovered technological shortcomings which influenced component capability and had an unfavorable impact on the system. The study identified those areas where advances in component technologies will contribute to significant improvements in SPS characteristics - performance, weight and/or volume, and mechanical integrity - within the constraints of reasonable production cost for the system. The research and development recommended to accomplish the desired technological advancements were documented, including time and cost estimates. A summary of the cost breakdown for each area of development is shown in Table III. The recommended research programs included reliability improvement for hydraulic components, high-speed electric motor starters, an air-cycle machine for ECS, and APU component improvement efforts. In particular, design, development, and qualification of an auxiliary power unit and an air turbine starter applicable to the helicopter requirement are recommended.

TABLE III. SPS COMPONENT COST DATA AND CHARACTERISTICS

| | Technology Level | APU and APU Start | Engine Start and Control | Cockpit Cooling Pack | Generators & Control Units | Hydraulic Power Packs | AGB | Total |
|---|---|---|---|---|---|---|---|---|
| Nonrecurring Costs - Million Dollars | 1970 Off-Shelf | .5 | .05 | .010 | .05 | .03 | .10 | .74 |
| | 1970 Tech. | 3.5 | .15 | .015 | .20 | .08 | .39 | 4.34 |
| | 1975 Tech. | 4.0 | .20 | .025 | .25 | .10 | .46 | 5.04 |
| | 1985 Tech. | 4.5 | .25 | .050 | .30 | .12 | .54 | 5.76 |
| Acquisition Cost per Prototype Ship Set - Thousand Dollars | 1970 Off-Shelf | 25 | 10 | 7 | 10 | 25 | 5 | 82 |
| | 1970 Tech. | 50 | 20 | 7 | 20 | 50 | 10 | 157 |
| | 1975 Tech. | 65 | 24 | 7 | 24 | 60 | 12 | 192 |
| | 1985 Tech. | 77 | 28 | 8 | 28 | 72 | 13 | 226 |
| Acquisition Cost per Production Ship Set - Thousand Dollars | 1970 Off-Shelf | 13 | 6 | 5 | 6 | 10 | 2 | 42 |
| | 1970 Tech. | 13 | 7 | 6 | 7 | 14 | 3 | 50 |
| | 1975 Tech. | 15 | 8 | 6 | 8 | 17 | 4 | 58 |
| | 1985 Tech. | 18 | 12 | 7 | 9 | 24 | 4 | 74 |
| Maintenance Man-hours per Flight Hour | 1970 Off-Shelf | .053 | .010 | .007 | .005 | .028 | .006 | .109 |
| | 1970 Tech. | .043 | .009 | .005 | .003 | .019 | .005 | .084 |
| | 1975 Tech. | .034 | .008 | .004 | .002 | .012 | .005 | .065 |
| | 1985 Tech. | .026 | .008 | .003 | .002 | .007 | .005 | .051 |
| Component Weight per Aircraft - Pounds | 1970 Off-Shelf | 123 | 42 | 26 | 56 | 26 | 55 | 328 |
| | 1970 Tech. | 111 | 36 | 26 | 56 | 21 | 50 | 300 |
| | 1975 Tech. | 72 | 31 | 25 | 48 | 18 | 45 | 239 |
| | 1985 Tech. | 52 | 27 | 24 | 36 | 14 | 43 | 196 |
| Equivalent Air-frame Weight - Pounds | 1970 Off-Shelf | 255 | 87 | 54 | 116 | 54 | 114 | 680 |
| | 1970 Tech. | 230 | 75 | 54 | 116 | 43 | 103 | 621 |
| | 1975 Tech. | 149 | 64 | 52 | 99 | 37 | 93 | 494 |
| | 1985 Tech. | 108 | 56 | 50 | 75 | 29 | 89 | 407 |

## INTRODUCTION

Increased military demands and uses of the helicopter in recent years have enlarged its role in Army operations. The experience gained from worldwide deployment of helicopters has shown that future rotary-wing aircraft must be totally self-sufficient for operations in many remote-field environments. Some of the most significant requirements dictated by these operations include:

1. Self-contained starting capability for all on-board systems, inflight as well as on the ground
2. Crew and equipment environmental conditioning
3. Secondary power subsystem checkout
4. Rapid reaction time to activate the aircraft
5. Emergency power generation
6. Multiple uses of the auxiliary power unit and other systems as sources of power
7. Management of power distribution and interfaces among functional and physical characteristics of the secondary power system
8. Best balance and optimization of hydraulic, electric, pneumatic, and mechanical power delivery methods
9. Mission success criteria and life-cycle costs in view of reliability, maintainability, vulnerability, and redundancy considerations
10. Main-engine starting capability with an inoperable auxiliary power unit
11. Growth capability of the secondary power system in keeping with expanding roles of the aircraft

In order to determine optimum SPS for the specified technology levels to satisfy these requirements, a program was followed as outlined below.

The contracted study included surveys of engine manufacturers to determine starting requirements and bleed capability of the helicopter main engines. Surveys of manufacturers of SPS components were also conducted to provide performance, weight, size, volume, and cost characteristics for the applicable technology levels. Combined with the substantial amount of data that Boeing had derived and correlated in previous programs, these data established the component technology base for the study.

A parametric APU cycle study was performed to calculate comparative design-point performance of nonregenerative and regenerative APU engines. Based upon prior research conducted by Boeing and performance analyses of the survey APU engines, an assessment of current component capability and planned improvements was made, to be used in the parametric performance studies. Shaft power and bleed capability of the parametric engines were defined.

Component arrangements and SPS concepts were generated to fulfill the aircraft secondary power requirements. Initially, the vehicle configuration was defined together with mission profiles. Table IV is the weight statement assumed for the aircraft. The basic mission is described in terms of power and speed as follows:

- 8 minutes at engine idle
- 20 minutes at Normal Rated Power
- 110 minutes at cruise at 150 knots

The various alternative functions of the secondary power system were analyzed, considering component power sharing, complexity of system design, and definition of redundancy requirements. The preliminary selection process reduced the number of SPS candidates, and the more promising ones, described in preliminary design drawings, were subjected to later in-depth evaluation and optimization.

A comparative evaluation of these selected systems determined the optimum system to fulfill the requirements for each technology level considered and incorporated components consistent with the technology time frame. Four possible options of the secondary power system were defined, to include the following functions:

- The baseline system, including the standard functions, but excluding the cockpit environmental control system (ECS) and main-engine starting provisions with an inoperable APU
- The baseline system, plus main-engine starting with an inoperable APU
- The baseline system, plus cockpit ECS
- The baseline system, plus cockpit ECS and starting with an inoperable APU

The component surveys, APU parametric study, and succeeding trade studies and evaluations uncovered technological shortcomings which influenced component capability and impacted

| TABLE IV. WEIGHT SUMMARY - 1970 BASELINE AIRCRAFT | |
|---|---|
| | Weight (lb) |
| Rotor Group | 1829 |
| Tail Group | 132 |
| Body Group | 2038 |
| Alighting Gear | 437 |
| Flight Controls | 775 |
| Engine Section | 52 |
| Propulsion | |
| Engines | 470 |
| Air Induction | 61 |
| Exhaust | 66 |
| Lubricating | 16 |
| Fuel System | 299 |
| Engine Controls | 20 |
| Drive System | 966 |
| Instruments & Navigation | 267 |
| Electrical | 216 |
| Electronics | 447 |
| Armament | 482 |
| Furnishings & Equipment | 380 |
| Secondary Power System | 545 |
| Weight Empty | 9498 |
| Fixed Useful Load | 718 |
| Fuel | 1428 |
| Troops | 2640 |
| Combat Equipment | 112 |
| Gross Weight | 14396 |

unfavorably on the total SPS performance, weight, and cost. The areas where technological advancements could provide significant improvements for future aircraft, the available technology in these areas, and the recommended research and development to accomplish the desired technological advancements were identified.

The program was organized into five work tasks, as follows:

- Task I - Surveys
- Task II - Parametric APU Cycle Study
- Task III - SPS Functions, Evaluation, and Preliminary Design
- Task IV - Comparative Evaluation
- Task V - Required Research and Development

Each task is described in a separate section of this report. The program conclusions are presented in the last section of the report.

## SURVEYS

The SPS study program was initiated by conducting a survey of main-engine companies and of applicable SPS component manufacturers. Dialogues were established with engine manufacturers to define the starting torque characteristics and the pneumatic bleed capabilities of their main-engine candidates. Major manufacturers of applicable SPS components were solicited by mail to provide pertinent data on their products, with particular emphasis on technological trends and innovations anticipated for the time frames being considered in the study.

### SURVEY OF MAIN-ENGINE COMPANIES

Three engines were considered as candidates for the design aircraft - each capable of producing approximately the required power and each programmed to be available in the required time period. The selected main-engine candidates were:

1. General Electric Company Model GE12/S1A

2. Pratt & Whitney Division Model ST9

3. AVCO Lycoming Division Model PLT-27

Data defining sea level and altitude engine starting power requirements and engine starting torque characteristics, as well as bleed capability, quality of bleed air, and the impact of bleed on engine performance, were obtained from each candidate engine manufacturer.

Minimum starter torque requirements established for the three engines are shown in Figure 4. They are based upon the most stringent requirement for each particular engine. Based upon the torque requirements shown, an SPS power requirement of 20 hp for main-engine starting was established for use in the subsequent SPS study tasks. The constant 20-hp torque-speed curve plotted in Figure 4 clearly shows that this power meets or exceeds the starting requirement of any candidate engine.

Main-engine compressor interstage bleed was considered to be more beneficial than compressor-exit bleed for inflight environmental control system (ECS) operation and possible cross-bleed engine starting concepts for the aircraft. Since the ECS and engine air-turbine starters would be designed to utilize a low-pressure air supply, the required throttling at bleed-air pressure ratios in excess of the low design values would waste energy and be reflected in a system power loss and increased specific fuel consumption (SFC). Interstage bleed would minimize these losses because the increases above system design pressure at the interstage bleed port (due to power variations resulting from different operational modes) are significantly

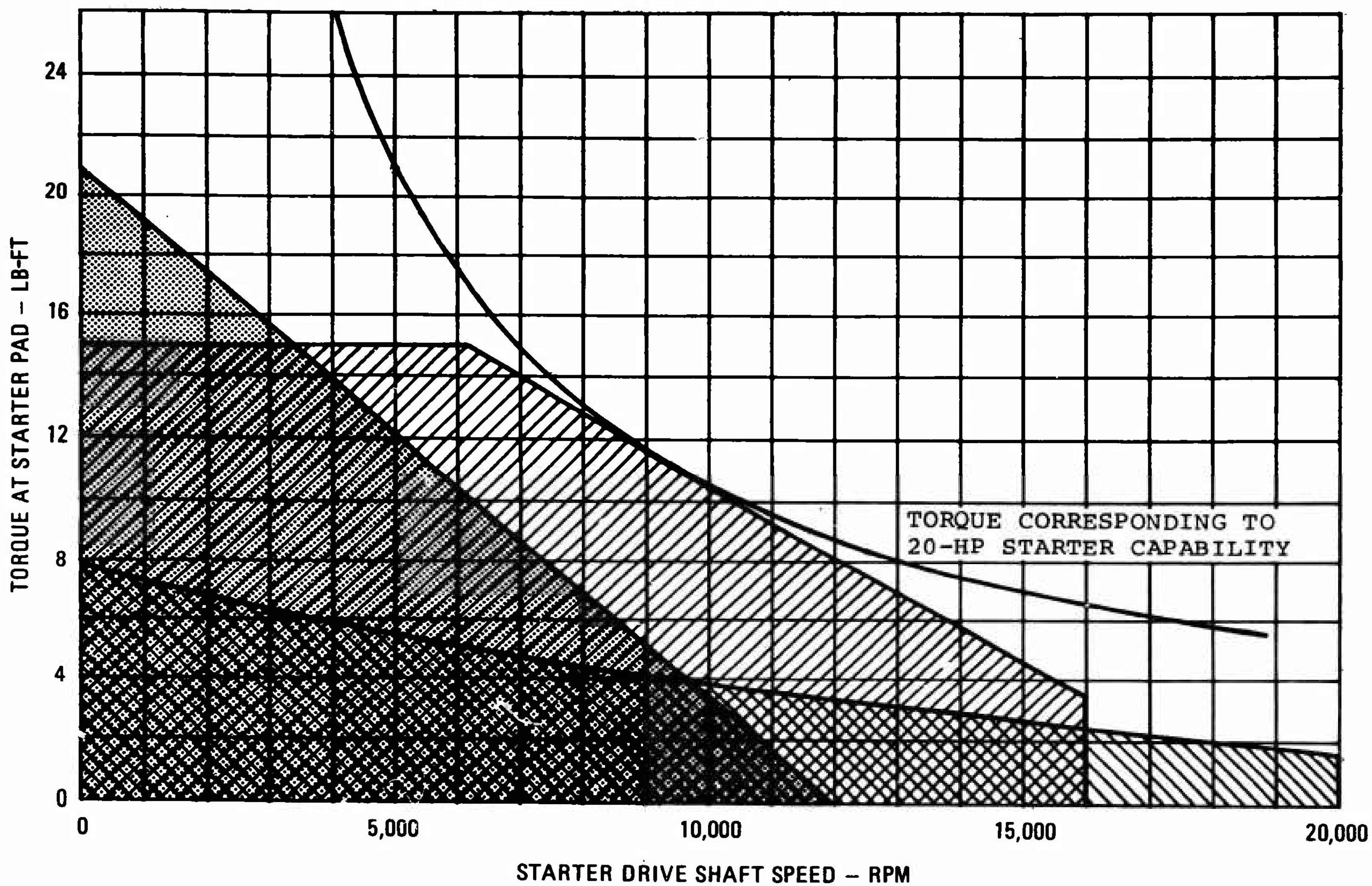



Figure 4. Main-Engine Starting Torque Requirements.

less than pressure variations at the compressor outlet. Furthermore, the lower pressure system would alleviate the special insulation and safety features that would be required for the higher temperature compressor-discharge bleed-air system.

All the candidate engine designs were considered to incorporate compressor interstage bleed-air extraction capability. The parameters describing estimated interstage bleed-air capability and quality provided by the manufacturers were averaged to obtain the representative characteristics in Figures 5, 6, and 7. Figure 5 shows the engine-inlet airflow, and the maximum bleed capability was 5.0 percent of engine airflow. Figure 6 presents the impact of bleed on engine power and SFC, and Figure 7 describes the quality (pressure and temperature) of the bleed air.

## SURVEY OF SPS COMPONENT MANUFACTURERS

Each solicitation mailed to the specialized component manufacturers included a questionnaire related to their product disciplines. These inquiries were designed to facilitate the assimilation and correlation of applicable technical data pertinent to their particular components of systems. Capacity, power, and/or operational range requirements anticipated for the components as utilized in the aircraft system were reflected in each questionnaire.

### Auxiliary Power Unit Survey

Preliminary design studies of the aircraft system and the assessment of its secondary power requirements seemingly dictated a small APU - probably in the vicinity of 1.0 to 2.0 lb/sec airflow. However, data were accumulated for small engines in general to verify performance and weight trends.

Table V lists the data for APU's and small engines readily accessible in publications for industry. The data items are familiar and largely self-explanatory. Equivalent shaft horsepower (ESHP) is perhaps the only relatively new term, and is equivalent to actual shaft horsepower plus air horsepower, the energy available in the bleed air (by ideal expansion of the bleed airflow from bleed pressure and temperature to ambient pressure, Figure 8).

Substantially more information was supplied by manufacturers in response to this survey, but because of its proprietary nature, it was omitted from the table. Instead such proprietary data has been presented in trend curves without identification to associate plotted points with specific engine models.

Plotted trends of APU data were predicated upon generally recognized relationships between engine performance parameters

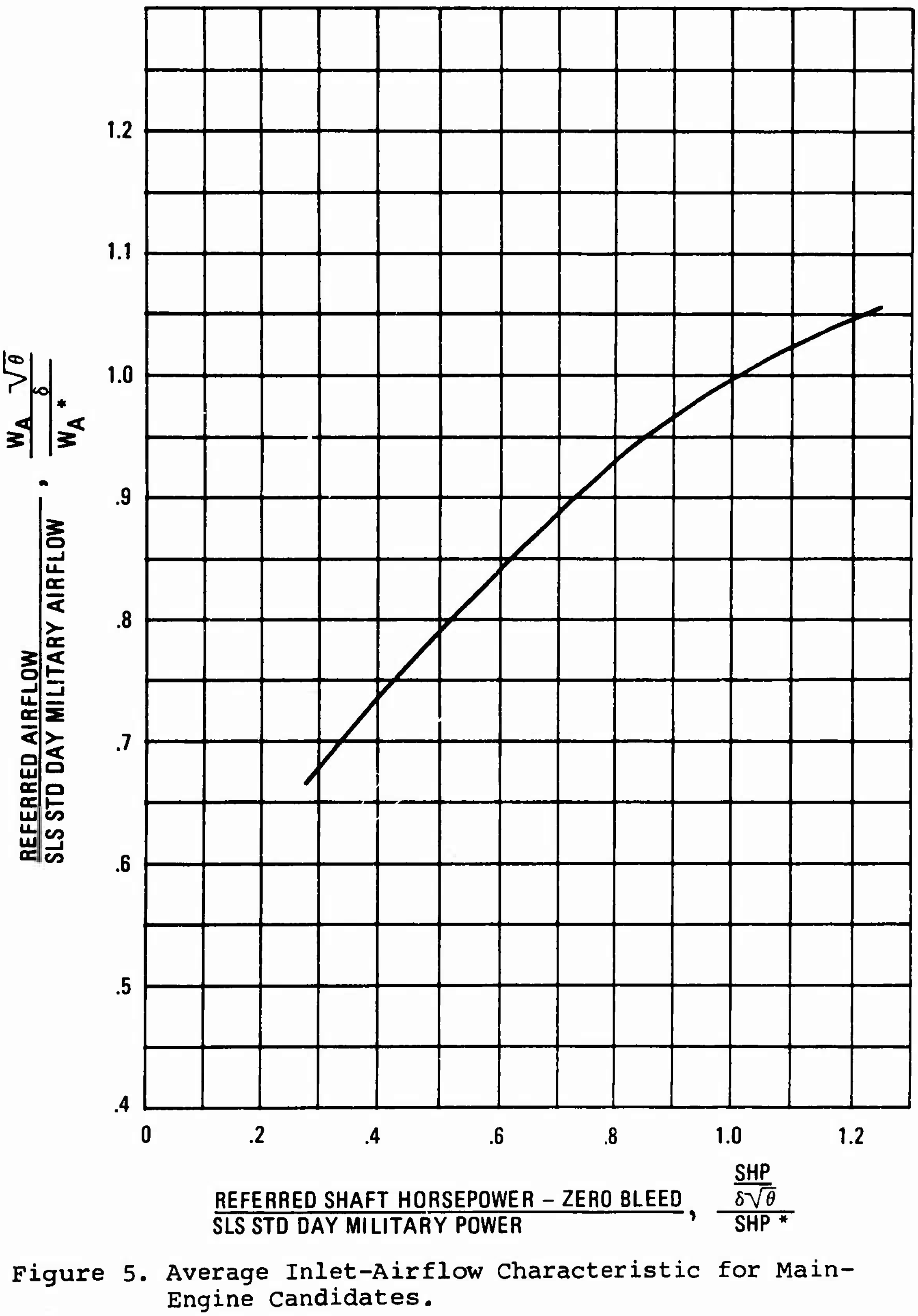



Figure 5. Average Inlet-Airflow Characteristic for Main-Engine Candidates.

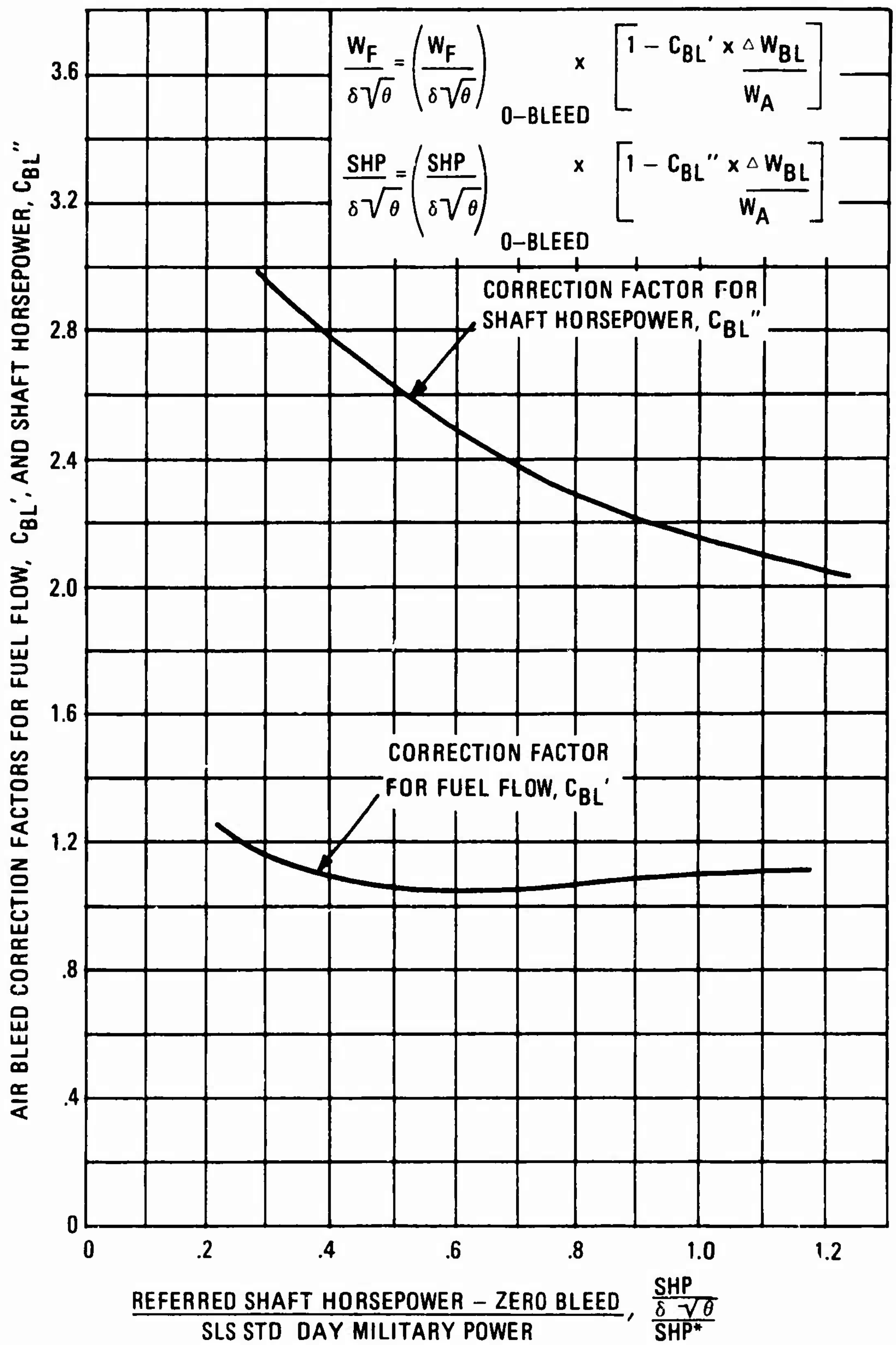



Figure 6. Average Main-Engine Bleed Correction Factors for Shaft Power and Fuel Flow (Interstage Bleed).

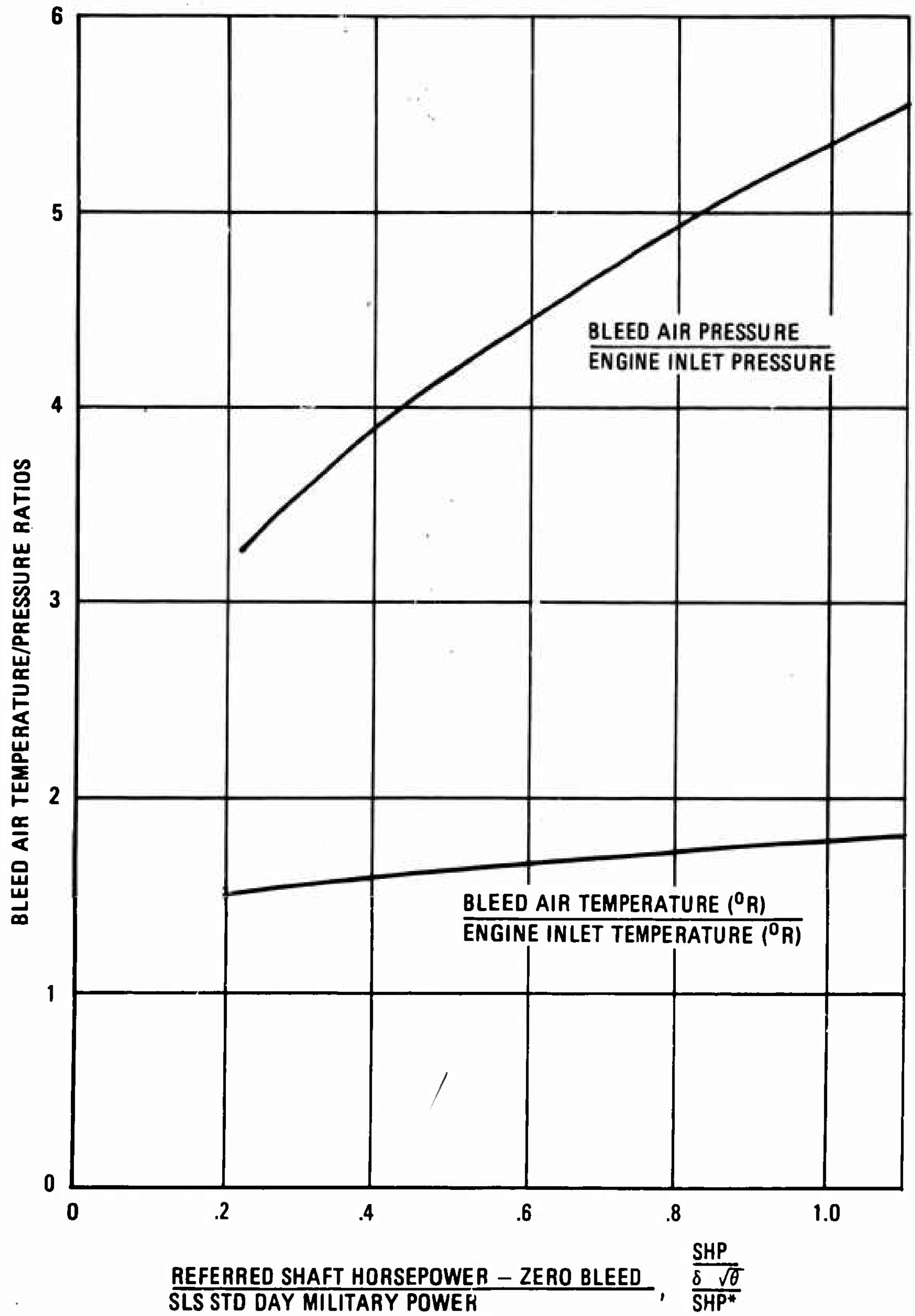



Figure 7. Average Main-Engine Bleed Air Pressure Ratio and Temperature (Interstage Bleed).

TABLE V. DESIGN PARAMETERS FOR AUXILIARY POWER UNITS AND SMALL TURBOSHAFT ENGINES

| Manufacturer | Model | Code (a) | Status (b) | Compr. (c) | Turb. (d) | $W_a$ (lb/sec) | CPR | TIT (°F) | $N_2$ (rpm) | SHP (O Bleed) (hp) | Bleed (lb/min) | $P_{b1}$ (psia) | $T_{b1}$ (°F) | ESHP (e) (hp) | Weight (f) (lb) | L/W/H (in) | Specific HP (g) (hp/lb/sec) | SFC (lb/hr/hp) | Power/Weight (hp/lb) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AIRESEARCH | GTP30-91 | 1 | Prod. | 1C | 1R | 1.3 | 3.1 | | 59200 | 85 | | | | | 87 | 21/18/16 | 65.4 | | .98 |
| | GTP30-95 | 2 | Prod. | 1C | 1R | | | | | | | | | | | | | | |
| | GTP30-141 | 3 | Prod. | 1C | 1R | 1.93 | 3.88 | | 59200 | 145 | | | | | 126 | 21/18/16 | 75.3 | .955 | 1.15 |
| | GTCP30-92 | | Prod. | 1C | 1R | | | | | | | | | | | | | | |
| | GTCP30-142 | | Prod. | 1C | 1R | 1.93 | 3.88 | | | | | | | | | | | | |
| | GTP36-7 | 4 | Prod. | 1C | 1R | 2.56 | 4.0 | | 58000 | 195 | | | | | 145 | 23/21/22 | 76.1 | .84 | 1.35 |
| | GTP36-60 | 5 | Prod. | 1C | 1R | | | | | | | | | | | | | | |
| | GTCP36-17 | | Prod. | 1C | 1R | 2.5 | 3.2 | | 58000 | | 68.5 | 42.5 | | | 150 | 23/21/22 | | | |
| | GTCP165-1 | | Prod. | 1C | 2A | | | | | | | | | | | | | | |
| | JFS100-2 | 6 | Prod. | 1C | 1A-1A | 1.72 | | | | 90 | | | | | 77 | 19/9/10 | 52.2 | | 1.17 |
| | T76-G-10 | 7 | Prod. | 2C | 3A | 6.2 | 8.6 | | | 715 | | | | | 310 | 45/20/27 | 116. | .60 | 2.30 |
| | TSE231-1 | 8 | Dev. | 2C | 1A-1A | | 8.9 | | | 474 | | | | | 174 | | | .60 | 2.72 |
| ALLISON | 250-C20 | 9 | Prod. | 6A,1C | 2A-2A | | 7.1 | | | 400 | | | | | 155 | 41/ /23 | | .63 | 2.58 |
| BOEING | 551 | 10 | Prod. | 1A,1C | 1A-1A | 4.44 | 5.72 | 1680 | 32000 | 400 | | | | | 385 | 39/27/24 | 90.2 | .75 | 1.04 |
| | 553-1 | 11 | Prod. | 1A,1C | 1A-1A | 4.93 | 6.48 | 1800 | 33400 | 490 | | | | | 385 | 39/27/24 | 99.5 | .73 | 1.27 |
| BUDWORTH | Brill | 12 | Prod. | 1C | 1R | | 2.8 | | 41000 | 90 | | | | | 100(f) | 28/20/15 | | 1.2 | .90 |
| | BUZZARD | 13 | Prod. | 1C | 1R-1A | | 3.0 | | 45000 | 130 | | | | | 120(f) | 28/20/15 | | 1.0 | 1.08 |
| DEUTZ | T216 | 14 | Prod. | 1C | 1R | 2.0 | 2.8 | 1500 | 50000 | 100 | | | | | 160 | | 50.8 | 1.32 | .63 |
| M.A.N. TURBO | 6012A | 15 | Prod. | 1C | 1R | | 3.0 | | 45[illegible] | 110 | | | | | 100(f) | 28/15/15 | | 1.26 | 1.10 |
| | 6012B | 16 | Prod. | 1C | 1R | | 3.0 | | 45000 | 75 | | | | | 100(f) | 28/15/15 | | 1.30 | .75 |
| | 6012B2 | 17 | Prod. | 1C | 1R | | 3.0 | | 42000 | 65 | | | | | 100(f) | 28/15/15 | | 1.43 | .65 |
| MICHIGAN RESEARCH | VECTOR | 18 | Prod. | 1C | 1A | 2.4 | 2.8 | 1500 | 48500 | 100 | | | | | 100 | 40/14/14 | 41.6 | 1.36 | 1.00 |
| ROVER | NAPTON | 19 | Prop. | 1C | 1R | .68 | 3.15 | | 94500 | 47 | | | | | 52(f) | 17/13/12 | 69.0 | 1.17 | .90 |
| | MYTON | 20 | Prod. | 1C | 1A | 1.45 | 2.9 | | 46000 | 75 | | | | | 133(f) | 19/19/29 | 51.6 | 1.3 | .56 |
| | RYTON | 21 | Dev. | 1C | 1R-1A | 1.33 | 3.8 | | 53000 | 86 | | | | | 57(f) | 19/8/8 | 64.6 | 1.1 | 1.51 |
| | WOLSTON | 22 | Prod. | 1C | 1A | 1.88 | 2.9 | | 46000 | 116 | | | | | 133(f) | 19/19/29 | 61.6 | 1.23 | .87 |
| | MARTON | 23 | Prod. | 1C | 1R-1A | 2.1 | 3.3 | | 40000 | 146 | | | | | 150(f) | 37/14/14 | 69.5 | .86 | .97 |
| SOLAR | T-62T-27 | 24 | Prod. | 1C | 1R | 2.1 | 4.2 | | 61248 | 110 | | | | | 84 | 25/ /13 | 52.4 | 1.05 | 1.31 |
| | T-62T-40 | | Dev. | 1C | 1R | | | | | | | | | | | | | | |
| | T-220 | | Dev. | 1C | 1R | | | | | | | | | | | | | | |
| | T-350 | | Dev. | 1C | 1R | | | | | | | | | | | | | | |
| TELEDYNE CAE | TS120 | 25 | Dev. | 1A,1C | 1R | 1.7 | 5.6 | | | | | | | | | | | | |
| | 141 | | Prod. | 1C | 2A | | | 1460 | 35000 | | 132. | 53. | | 200. | 241(f) | | | 1.50 | |
| | 142-1 | | Prod. | 1C | 2A | | | | | | | | | | | | | | |
| UACL | PT6B-9 | 26 | Prod. | 3A,1C | 1A-1A | | 6.0 | | 33000 | 500 | | | | | 245 | 60/ /19 | | .69 | 2.04 |
| WILLIAMS RESEARCH | WR9-2 | | Prod. | 1C | 2A | | 4.0 | | | | 32. | 54. | | | 73 | 28/14/14 | | | |
| | WR9-4 | | Dev. | 1C | 2A | | 4.0 | | | 100 | | | | | | 29/14/14 | | | |
| | WR9-7C | | Dev. | 1C | 2A | | | | | | | | | | | | | | |

a. Code number identifies spot data points on trend curves.
b. Status - production, development, or proposal.
c. Compressor/turbine configuration: C-centrifugal; A-axial; R-radial; A,C-single shaft axial/centrifugal combined; A-A-two shafts, separate axial stages.
d. ESHP = SHP+AHP (Power available by ideal expansion of bleed air from bleed temperature and pressure to ambient pressure).
e. Dry weight including accessories and gearbox.
f. No gearbox included in dry weight - high-speed output shaft.
g. Specific horsepower is shaft horsepower divided by inlet airflow, hp/lb air/sec.

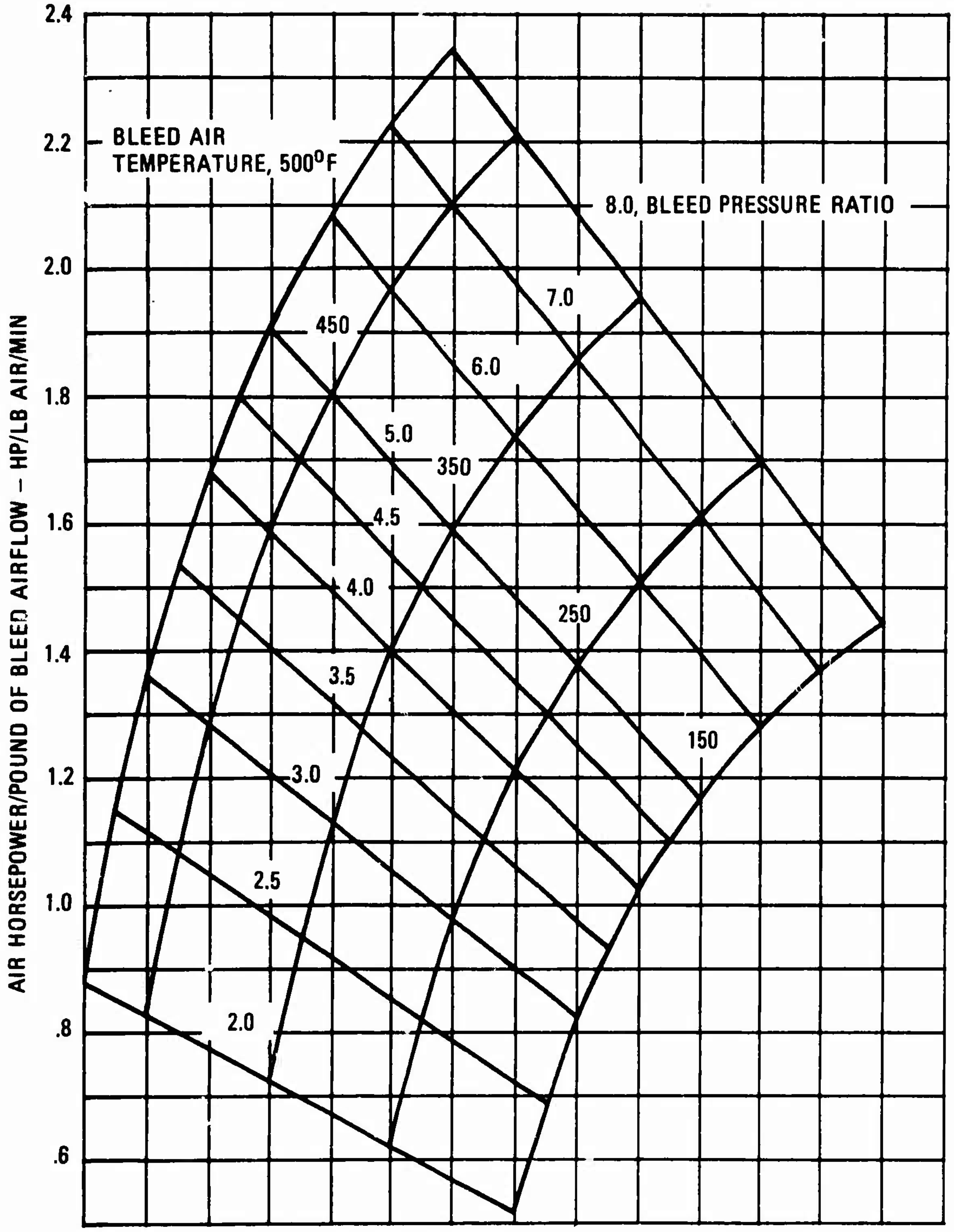



Figure 8. Bleed Air Horsepower for Each Pound per Minute of Bleed Airflow.

and the thermodynamic parameters, compressor pressure ratio and turbine-inlet temperatures:

1. Primarily, SFC improves with increasing pressure ratio, and it is only secondarily dependent on turbine temperature - particularly for the narrow range of temperatures that define a technology state of the art.

2. Specific power (shaft horsepower divided by compressor airflow) increases with turbine inlet temperature, and is dependent to a much smaller degree upon pressure ratio.

A large value of specific power is equivalent to a lower airflow and smaller engine for a given power requirement. Consequently, since specific power is essentially a function of turbine-inlet temperature, engine power-to-weight ratio is also dependent on turbine temperature.

Figures 9, 10, and 11 present SFC, specific power, and power-to-weight ratio trends for APU's and small engines. The solid symbols represent the larger engines considered and the open symbols, the smaller ones, with 2.0 lb/sec airflow as the dividing line between small and large. The numbers associated with individual points refer to the code designation in Table V; non-numbered points are proprietary data for other APU engine models. The "typical shaft engine trend" curves were drawn from calculated data to provide a comparison with the trends indicated by the real-engine points. The sample of real-engine data was small but generally corroborated the calculated curves. The trend curves provided the necessary correlation of pertinent APU characteristics to be used as a baseline for the subsequent parametric APU cycle study.

The request for data on anticipated improvements in APU component performance and weight compatible with the 1985 production time period and the impact of these improvements on size, weight, and performance characteristics of APU's elicited only the most generaly response from the manufacturers. Certain basic ground rules seemed typical among the various responses:

1. Thermodynamic design parameters - compressor pressure ratio and turbine inlet temperature - will increase for improved performance.

2. New APU's will emphasize reliability and producibility.

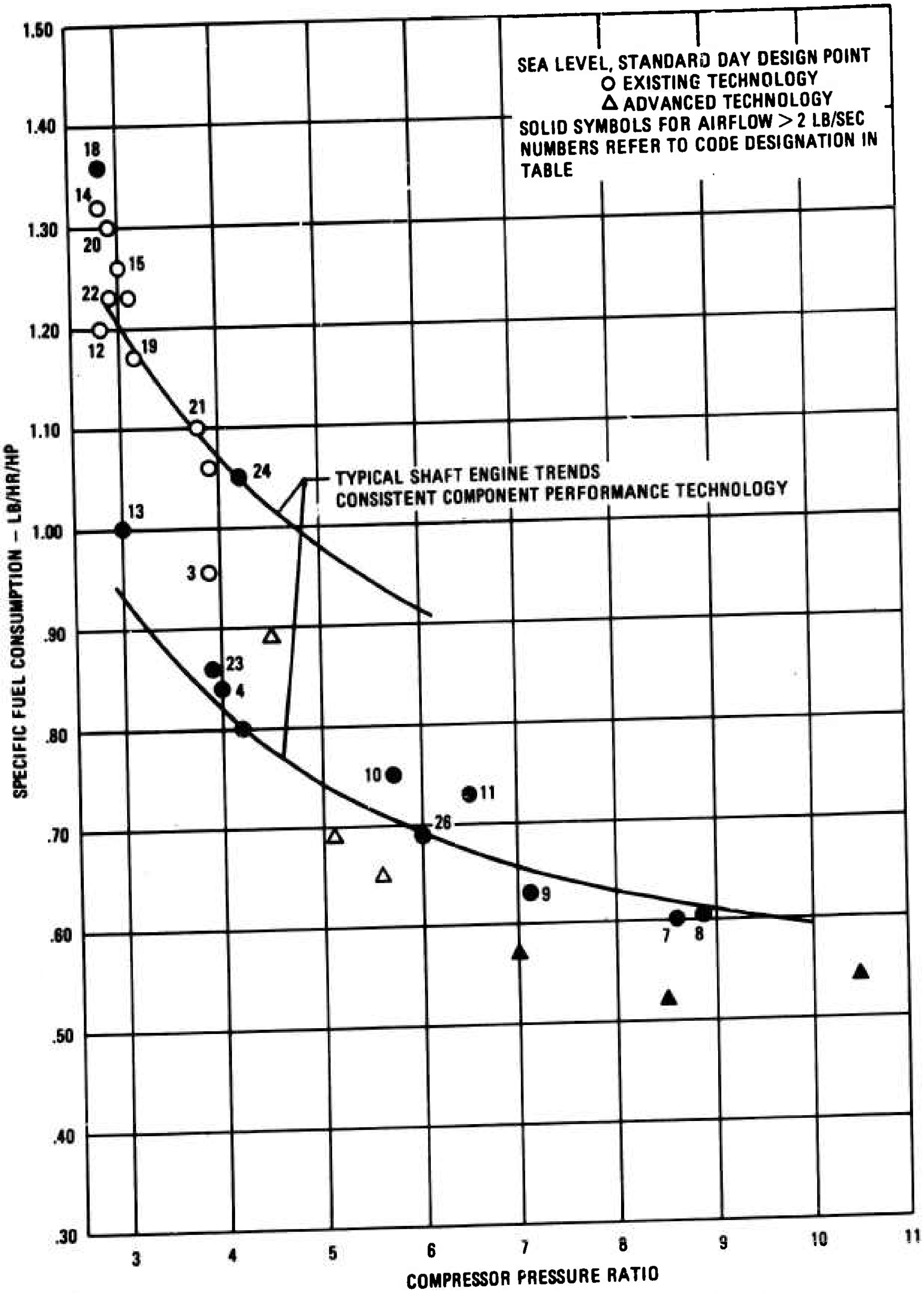



Figure 9. SFC Trends for Shaft-Power APU's and Small Engines.

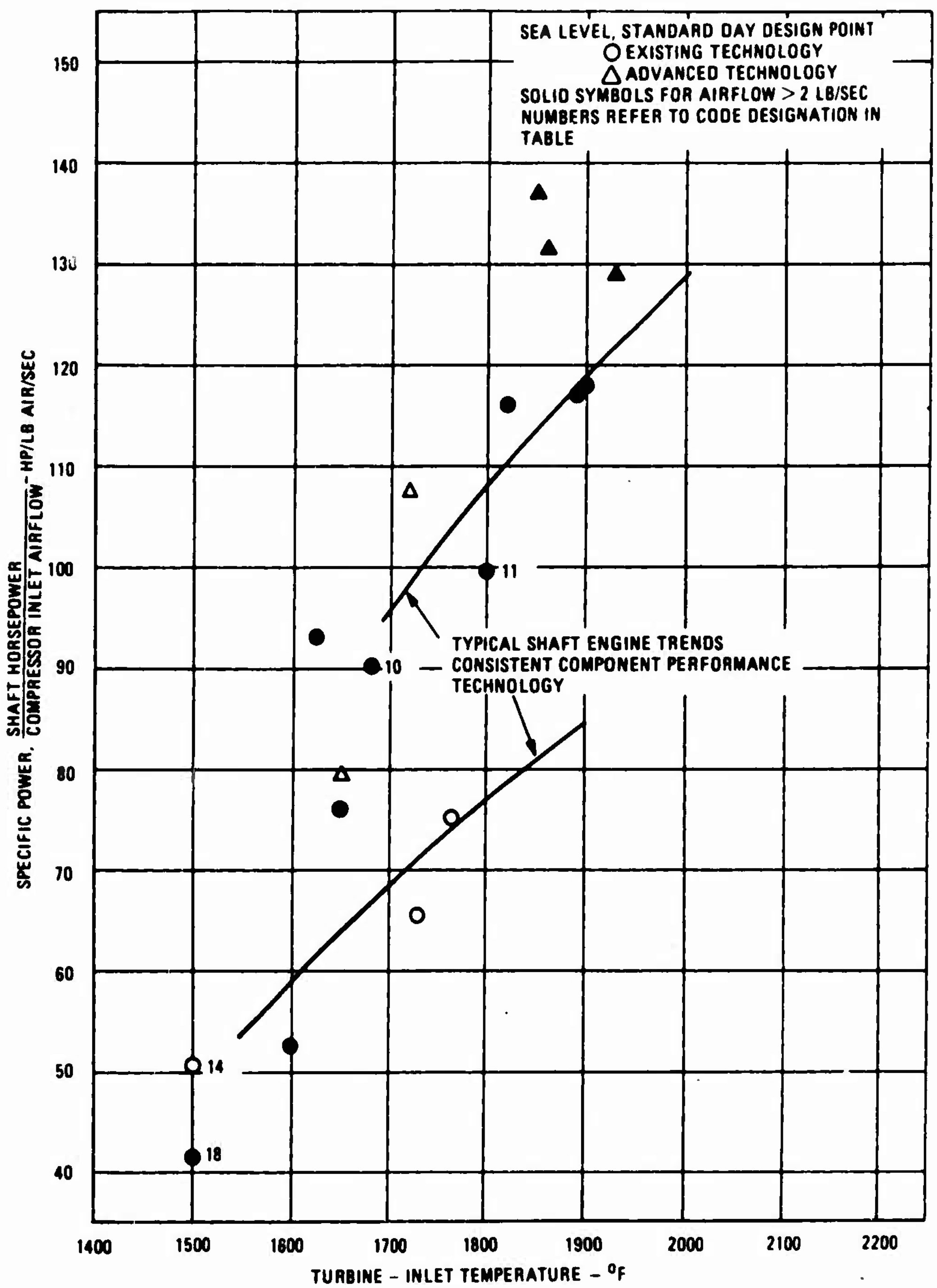



Figure 10. Specific Power Trends for Shaft-Power APU's and Small Engines.

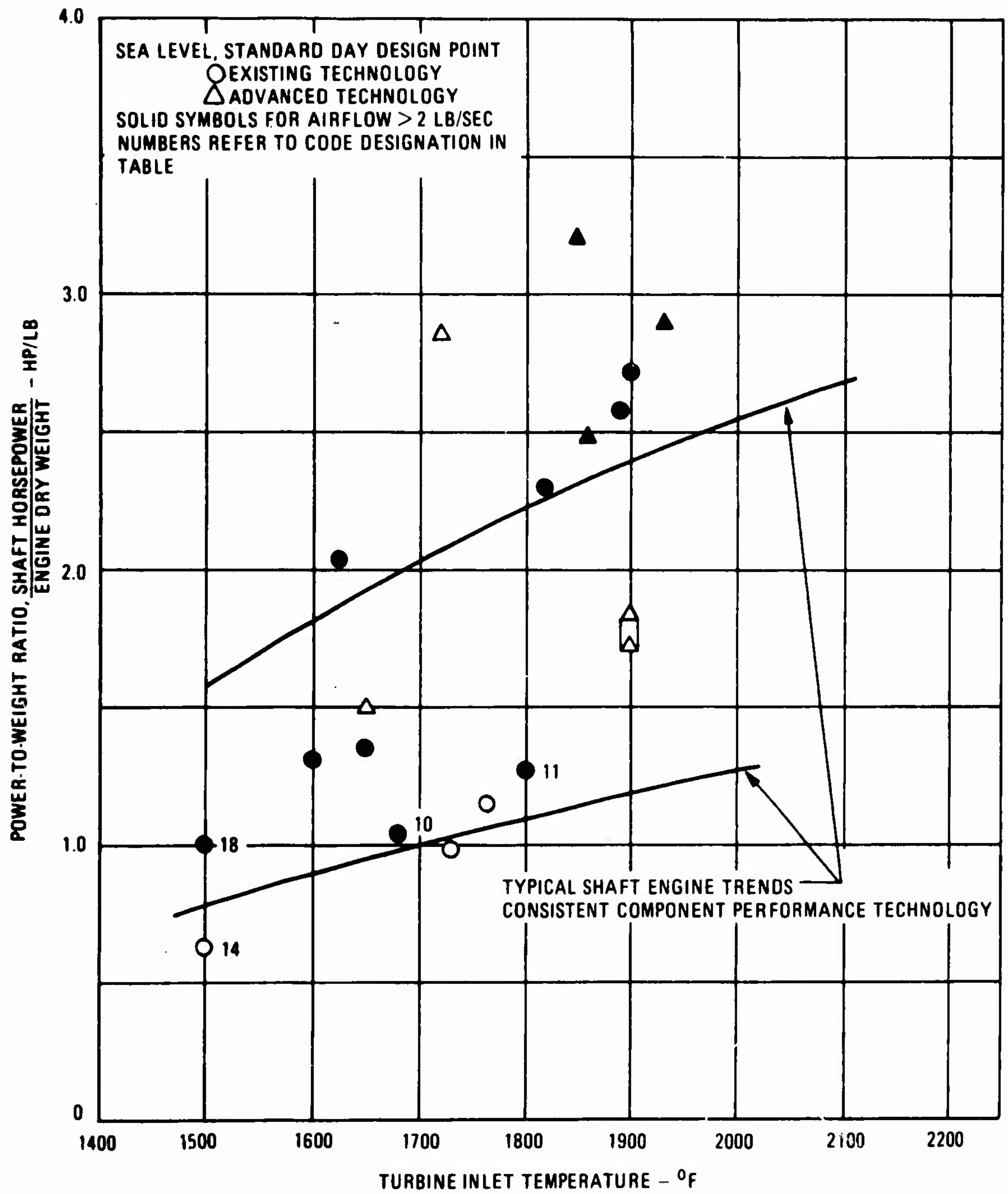



Figure 11. Power-to-Weight Ratio Trends for Shaft-Power APU's and Small Engines.

3. Emphasis on cost will be carried over into material selection - unproven exotic materials for low weight or high-temperature strength properties will be avoided.

Improvements in APU performance will result from both increased compressor pressure ratio and turbine inlet temperature, as well as improved component efficiencies. It is anticipated that these changes will result in 20 percent lower SFC's for 1975-technology engines at the same pressure ratio, and perhaps 10 to 15 percent further reduction to the 1985-engine performance. Higher pressure ratios will, of course, produce even greater SFC reductions, consistent with the usual shaft-engine trends.

Despite the emphasis on cost for future APU's, improvements in component weights coupled with higher specific power at constant turbine inlet temperature as a result of improved component performance will combine to produce improvements of 40 percent in power-to-weight ratio for the 1975-technology APU, compared to existing-technology engines. Similar improvements can be anticipated between the 1975-technology and 1985-technology APU's.

The net result of these various improvements would seem to be that 1985-technology small APU engines would have performance and weight characteristics that conform to the trend data for the larger small engines (airflow greater than 2 lb/sec) in Figures 9 through 11.

## Hydraulic, Pneumatic, and Electrical Components Survey

A variety of responses were obtained from the major electrical, hydraulic and pneumatic component manufacturers surveyed. However, the responses provided sufficient and adequate data for the subsequent synthesis of secondary power systems and trade-off studies.

A considerable amount of component technology information and forecasts was submitted in narrative form, particularly for small components which were not envisioned to be substantially improved within the time frame considered. The data received in graphical or numerical form pertained to the major SPS power components, such as hydraulic motors, starters, and pumps; electrical integrated drive generators (IDG), generators, and generator control units; pneumatic starters;

and cartridge pneumatic starters. Characteristic trend data submitted for a 1-to 3-ton refrigeration capacity ECS were based on the air-cycle design currently in use on the Bell Cobra helicopter.

The data submitted by the various contributors were assimilated into trend curves for each particular component. Typical curves are pictured in Figures 12 through 15, which describe the weight, volume, cost, reliability, and maintainability parameters for current (existing technology) hydraulic motors and pumps and forecasted trends in these parameters. This and similar compilations of data for the various SPS components formed the basis for establishing component comparison factors, used in subsequent trade-off studies among the secondary power systems which were synthesized. The following paragraphs discuss some of the pertinent information contributed by the SPS component manufacturers in relation to their own products.

The technological improvements envisioned for hydraulic power units (pumps, motors, starters) were more related to the utilization of higher hydraulic pressure levels predicted for the future than to any anticipated improvement in component efficiency or performance. A 1500-psi flight hydraulic system was selected for the baseline aircraft since this pressure was determined to be best suited to flight control actuator force and stiffness requirements. Because of the small capacity of the flight pumps, there is not a significant weight difference between 1500 and 3000-psi pumps for this application. However larger pumps, such as those used to power hydraulic starting of engines, would be designed for at least 3000 psi, and in fact would probably be 4000 psi for existing technology. All the contributing manufacturers considered the 3000-psi hydraulic system as current technology and the 4000-psi system as advanced technology. A majority expected increased use of the 4000-psi systems in 1975 and its ultimate standardization by 1985. Advanced systems in 1985 would utilize 6000-6500 psi pressure levels. Fly-by-wire control systems were envisioned for advanced 1985 aircraft, utilizing complete and separate hydraulic power package units at each actuator.

No significant technological improvements were envisioned for hydraulic and pneumatic components such as valves, regulators, actuators, and reservoirs. However, the current emphasis on maintainability and reliability should be reflected in the future designs of these components.

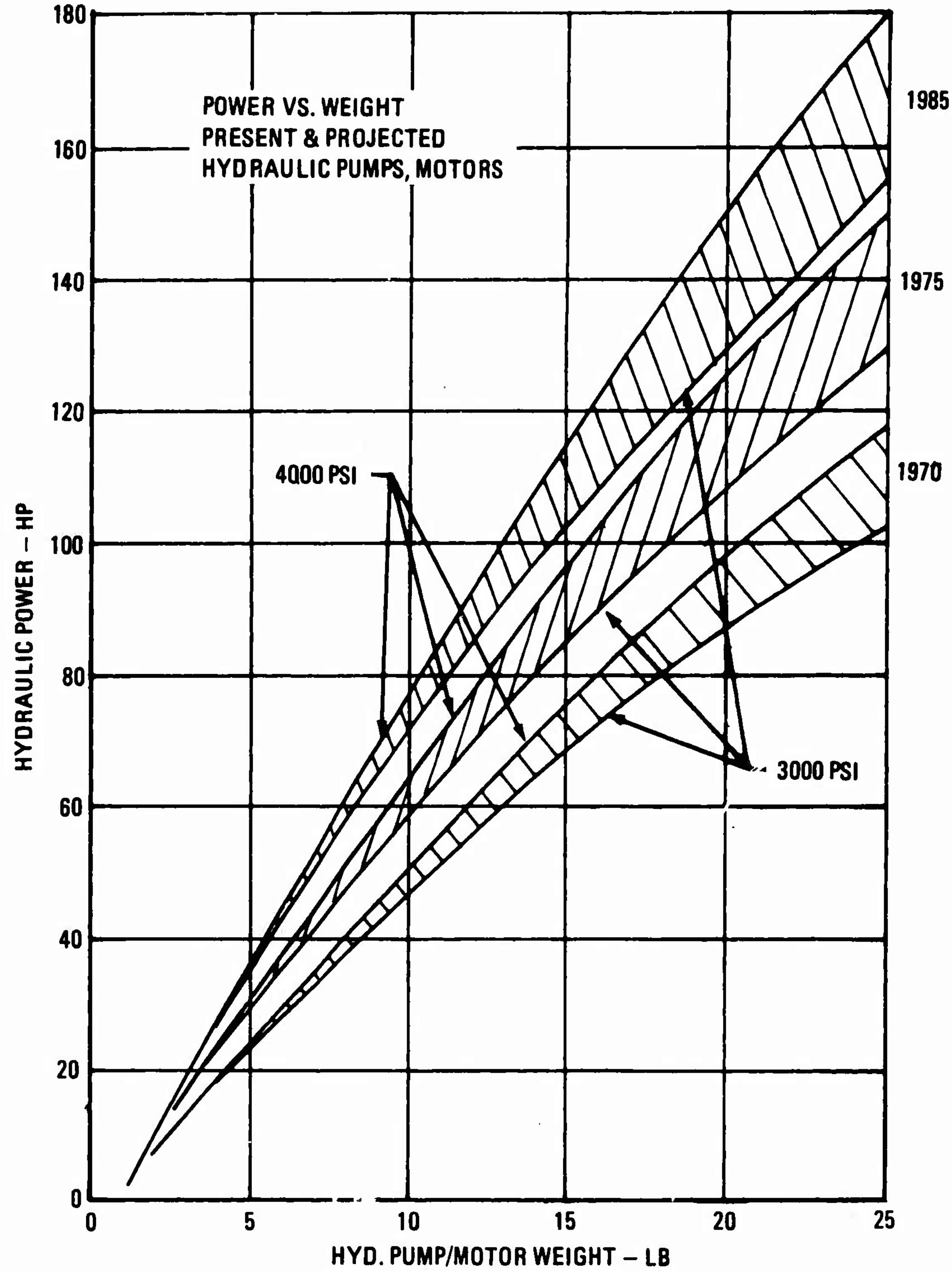



Figure 12. Weight Trend Data for Hydraulic Motors and Pumps.

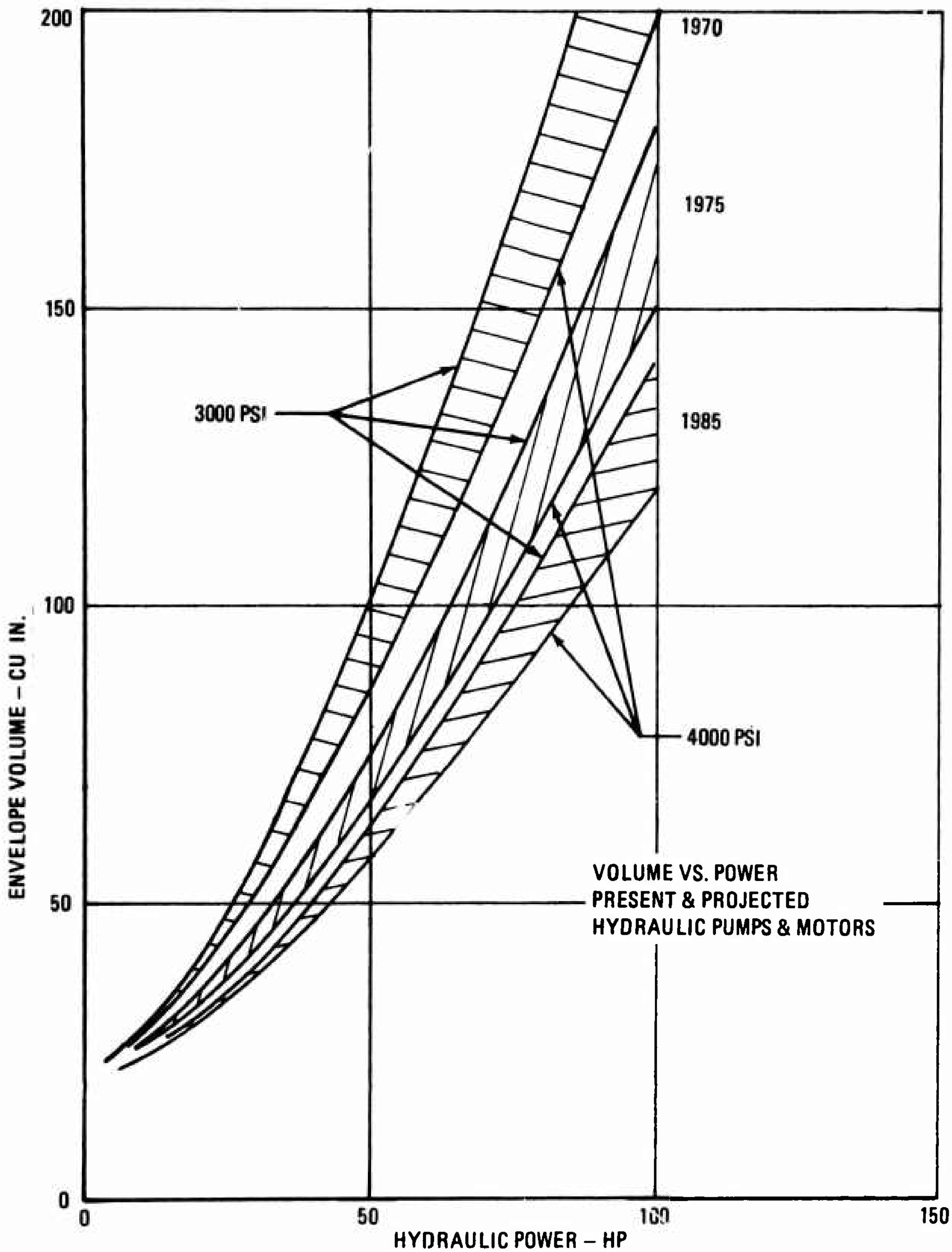



Figure 13. Volume Trend Data for Hydraulic Motors and Pumps.

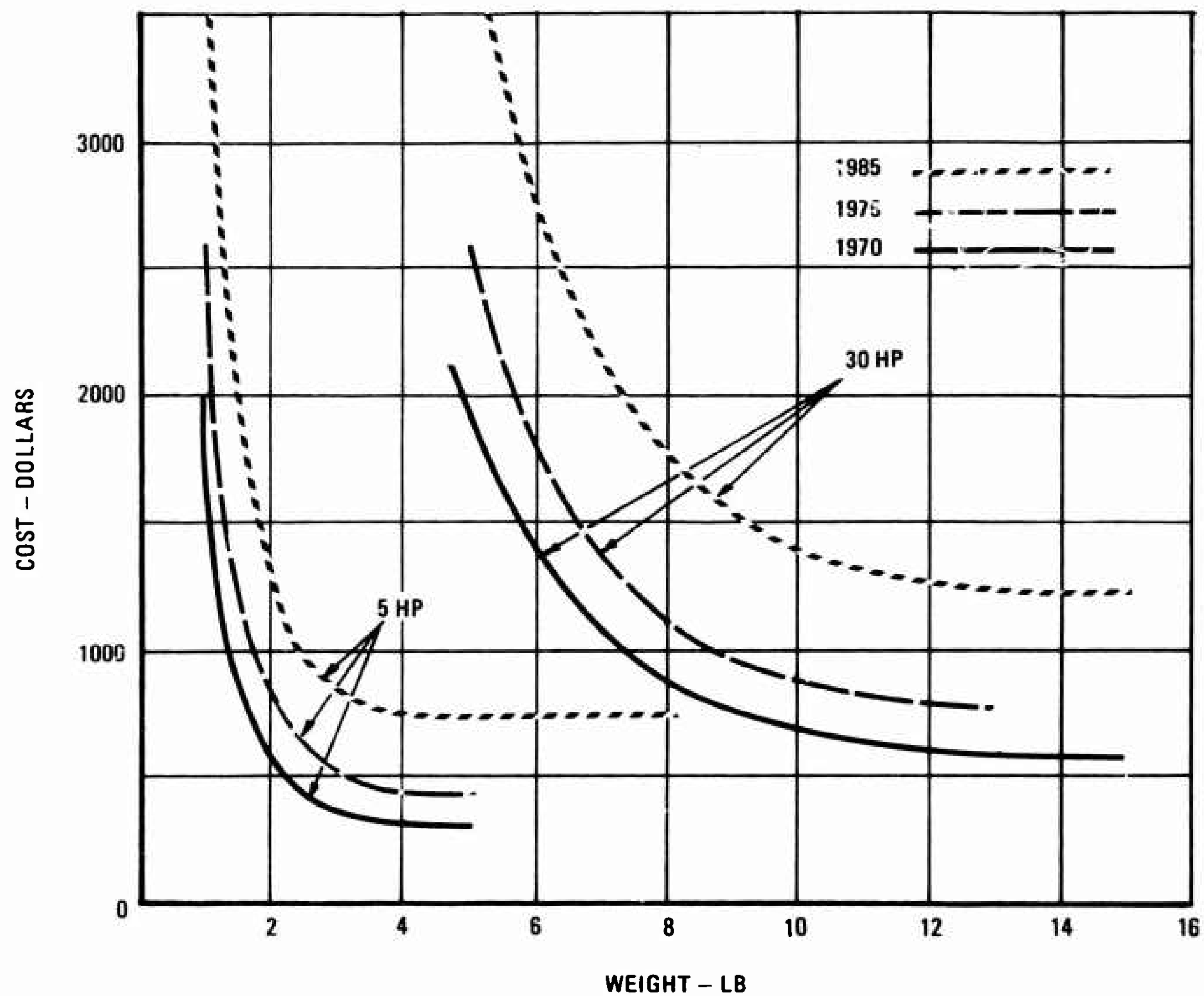



Figure 14. Cost Trend Data for Hydraulic Motors and Pumps.

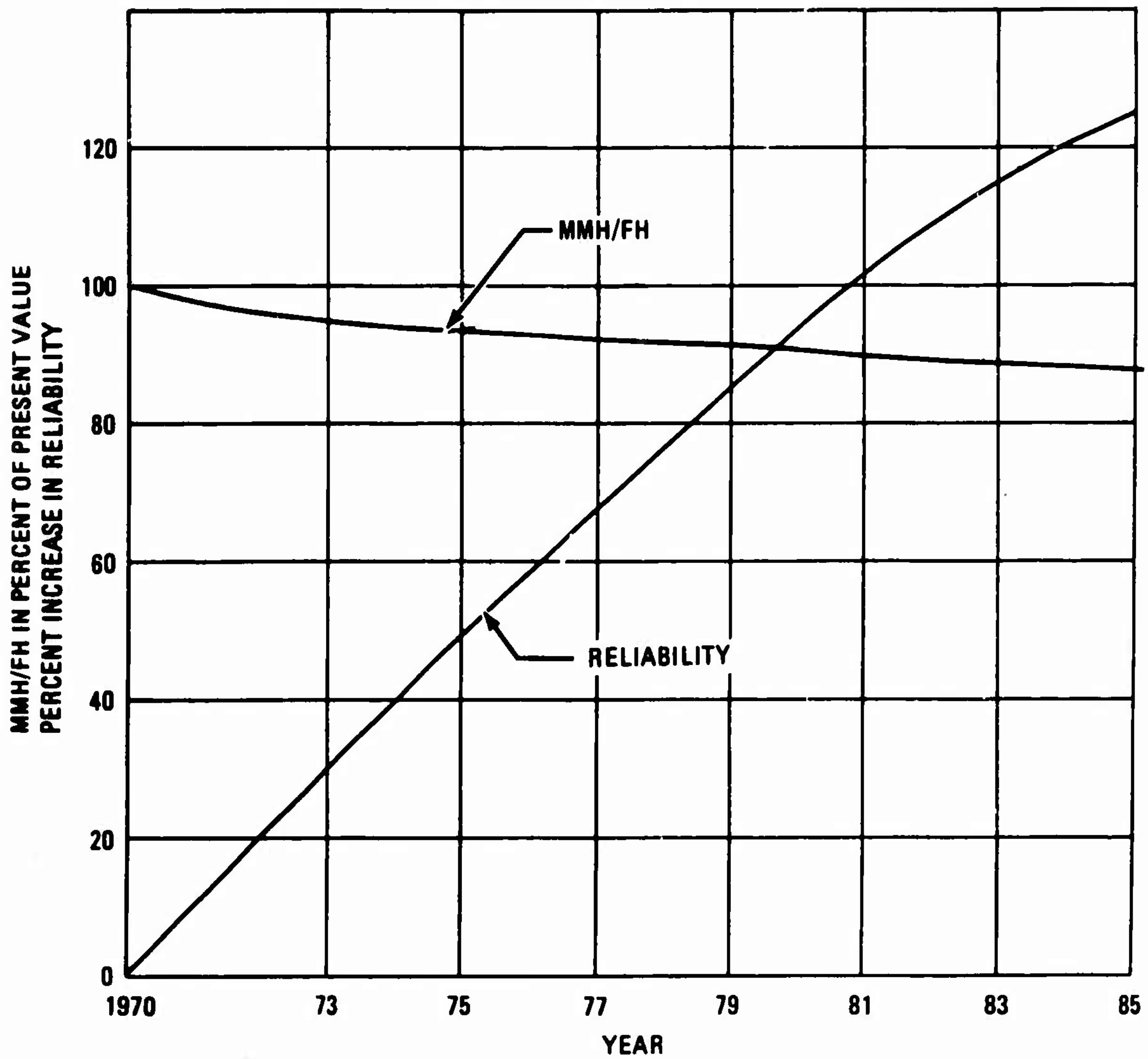



Figure 15. Reliability and Maintainability Trend Data for for Hydraulic Motors and Pumps.

Currently there is no air turbine starter designed specifically for main engines in the power class considered for this study. Several manufacturers proposed immediate off-the-shelf starter designs by modifying only the turbine flow area of air turbine starters currently used on much larger engines. Although expedient, this would penalize seriously the starting system in air horsepower requirements and in weight.

Immediate technological advancements proposed for generator designs included incorporating the oil-spray cooling technique currently utilized on the constant-speed IDG units. All the manufacturers responding to the electrical survey submitted characteristic data for current-technology generators which would utilize this design principle. These vendors cited the significant weight, size and performance advancement in this generator design. Each, however, has minimized the fact that these designs require a pumping and heat sink source for the cooling air spray. The magnitudes of the cited generator gains should be modified accordingly in any comparative study.

Inquiries failed to generate any data for electric starters or starter-generator units. Surveyed manufacturers indicated that little or no funding is being allocated to conduct research and development of high-speed motor designs for this application.

The development of sealed nickel-cadmium batteries could improve the maintainability of this type of battery.

The development of solid-state switching and circuit breaker devices was expected to improve the power distribution systems utilized in aircraft.

## PARAMETRIC APU CYCLE STUDY

For selected engines from the Task I survey, shaft power and SFC and pertinent pressures and temperatures at various reference stations were obtained. Design-point performance analyses of the APU candidates were conducted to determine component efficiencies, losses, parasitic airflows, and accessory powers which were consistent with the quoted thermodynamic parameters. The component data were, in turn, correlated with data compiled in prior studies of small engines. From these correlations were developed the functional relationships between component performance, pressure ratio, and size, and the relationships between component configuration and state-of-the-art (and their impact on performance), to determine component trends. The component trend data were used in calculating the comparative design-point performance - both shaft power and bleed capability - of nonregenerative and regenerative APU engines (Task II).

The helicopter secondary power requirements dictated a small APU, in the vicinity of 1.0 to 2.0 lb/sec airflow. The component performance assumptions for the parametric study and the overall APU engine performance reflected this anticipated small size.

Various alternative component design concepts were evaluated to determine their impact on engine performance and weight, and potential APU improvements for each level of technology.

## COMPARATIVE DESIGN-POINT PERFORMANCE

Design-point specific power and specific fuel consumption were calculated for the range of compressor pressure ratios and turbine inlet temperatures considered in the parametric APU cycle study, for nonregenerative, simple-cycle APU engines and for regenerative engines with 0.60 and 0.90 effectiveness. Specific power is defined as the shaft power produced per pound of compressor inlet airflow. Bleed-air capability of these parametric engines (with zero shaft power output) was calculated and expressed as a fraction of inlet airflow.

The parametric study was conducted with selected ranges of the engine parametric and selected component configurations as a function of the level of technology, according to the values in Table VI.

| TABLE VI. APU ENGINE CYCLE PARAMETERS AND COMPRESSOR CONFIGURATIONS | | | | | | |
|---|---|---|---|---|---|---|
| Level of Technology | 1970 | | 1975 | | 1985 | |
| Compressor Pressure Ratio & Configuration* | 4:1 | C | 4:1-8:1 | C | 4:1-12:1 | C |
| | 6:1-8:1 | A,C | 12:1 | A,C | 16:1-20:1 | A,C |
| Turbine-Inlet Temperature, $^{o}F$ | 1700-1900 (Uncooled) | | 1900-2100 (Cooled) | | 2100-2400 (Cooled) | |
| Regenerative Engine Pressure Ratio | 4:1-6:1 | | 4:1-10:1 | | 4:1-10:1 | |
| Regenerator Effectiveness | .60 - .90 | | .60 - .90 | | .60 - .90 | |

*C = Centrifugal Compressor
A,C = Axial-Centrifugal Compressor

The ambient condition selected for the parametric engine design point was sea level, 130$^{o}$F, equivalent to 1600 feet, 95$^{o}$F. This was assumed to be the maximum which would be encountered in the field. Acceptable limits for the air temperatures in the SPS pneumatic ducts, in conjunction with the 130$^{o}$F inlet temperature, established the allowable pressure ratio at the bleed port for bleed-air machines - air was extracted at a 4:1 pressure ratio (see Appendix I).

## Component Performance

Component data consistent with the tabulated thermodynamic parameters, the component configurations, and the levels of technology were used to generate parametric engine performance. Compressor and turbine efficiencies and turbine cooling-air requirements, correlated with manufacturers' published trend data as a function of significant thermodynamic parameters, are included in Appendix I, together with other component efficiencies, pressure losses, parasitic airflows, and accessory powers assumed in generating APU performance. The component performance assumptions for the parametric study all reflect the anticipated small size of the APU engine.

## Correlation with APU Trends (Task I)

The trends of sea level, standard day specific power and SFC in Figures 16 and 17 (note the symbols which represent specific engine models and the curves labelled "TYPICAL SHAFT ENGINE TRENDS") were developed from the characteristics of APU's and small engines obtained in the Task I survey. The format of Figures 16 and 17 was predicated upon generally recognized relationships between engine performance parameters and the thermodynamic design parameters, compressor pressure ratio and turbine-inlet temperature:

1. Primarily, SFC improves with increasing pressure ratio, and it is only secondarily dependent on turbine-inlet temperature.

2. Specific power increases with turbine-inlet temperature, and it is dependent to a much lesser degree upon pressure ratio.

Engine size and the size of individual components, which influences their achievable performance, have a substantial impact on the relative performance of the very small APU's and the somewhat larger small engines. As in previous Figures, 2.0 lb/sec airflow was arbitrarily taken as the dividing line between small (open symbol) and larger (solid symbol) engines.

The component data assumptions used in the parametric APU cycle study were used to generate engine performance at sea level, standard day ambient conditions, and the resulting parametric APU performance was plotted in Figures 16 and 17, also. Performance for parametric APU's with existing technology was reasonably consistent with the trends for the smaller APU's. Similarly, performance for the 1985-technology parametric APU's was reasonably consistent with trend data for present-day larger small engines. It was assumed that size effects in the small APU's envisioned for this application would preclude achieving the levels of performance predicted for advanced-technology engines larger than 2.0 lb/sec. Consequently, SFC and specific power for the present-day engines larger than 2.0 lb/sec were selected as limits which could be achieved in the 1985-technology APU's.

Considering the parametric engine performance in Figure 16 for APU's with existing technology, the range in SFC values at any compressor pressure ratio reflects the influence of changes in turbine-inlet temperature. Changes in turbine-inlet temperature have much less effect on SFC for the 1975- and 1985-technology engines. Also, in Figure 17, for APU's with a given level of technology, the range of values of specific power at a given turbine-inlet temperature is a result of changes in pressure ratio. The higher pressure

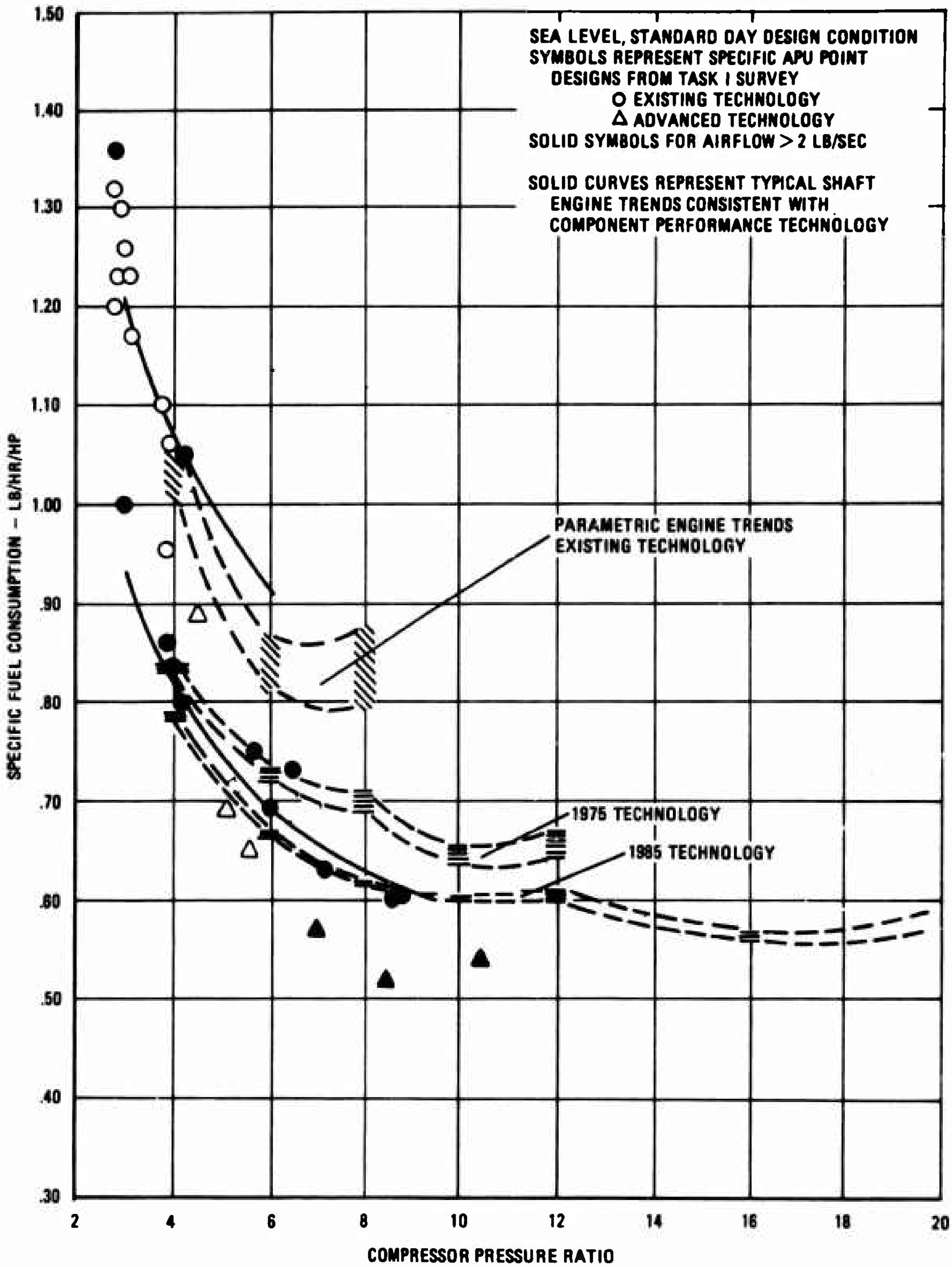



Figure 16. Correlation of Parametric APU Specific Fuel Consumption With APU-Engine Trends (Sea Level, Standard Day).

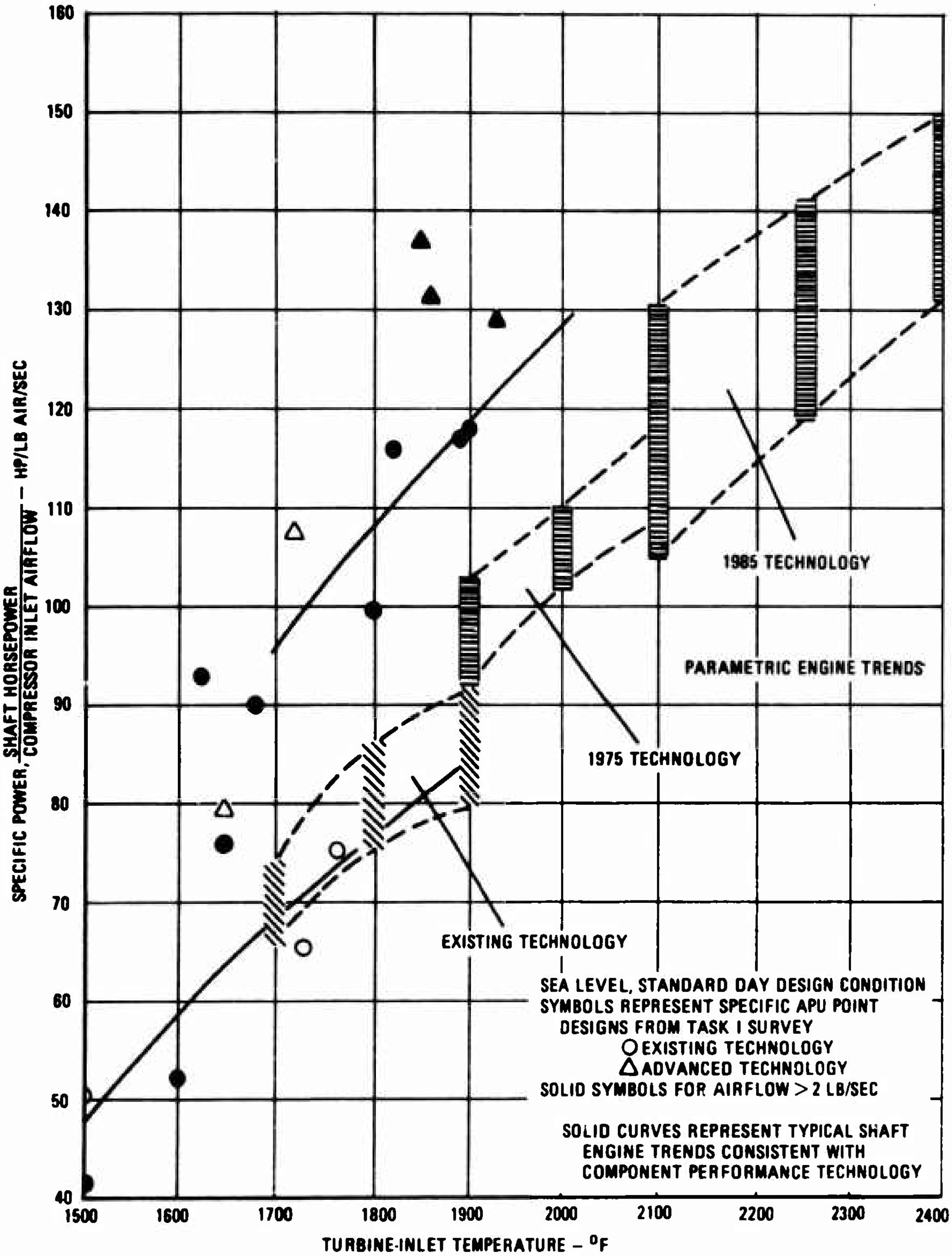



Figure 17. Correlation of Parametric APU Specific Power With APU-Engine Trends (Sea Level, Standard Day).

ratios are much beyond the optimum values from the viewpoint of maximum specific power, however. If consideration were given only to the more moderate pressure ratios for each level of technology, the range of parametric engine specific powers in Figure 17 would be reduced considerably.

## Parametric Study Results

Figure 18 presents the performance of the simple-cycle engines as shaft-power APU's for the three levels of technology, and Figure 19 presents bleed capability. The comparatively low component efficiencies resulted in low pressure ratios for optimum specific power and SFC, for all levels of technology. There were discontinuities in the plotted data for the 1975- and 1985-technology APU's, attributed to the change from centrifugal to axial-centrifugal compressor configuration and the attendant changes in efficiency.

Similarly, Figures 20 through 23 present the performance of regenerative parametric APU engines, with effectiveness values of 0.60 and 0.90. The high ambient temperature at the design point coupled with the low levels of component efficiencies limited the potential benefit from regeneration, and the pressure losses and leakage flows associated with the regenerator limited its potential benefits still further. At the lower turbine temperatures associated with existing technology engines, the effectiveness of 0.60 did not compensate for penalties to cycle performance resulting from regenerator losses, and only the effectiveness of 0.90 offered potential improvement. In general, regenerator leakage and pressure losses penalized engine performance sufficiently for all levels of technology, so that only high values of effectiveness seemed to offer enough improvement in performance to warrant the complexity of a regenerator.

## APU CONFIGURATION TRADE-OFFS

Virtually all of the small APU's of present technology are single-shaft nonregenerative machines, with radial compressors and radial turbines. For applications requiring both a source of pressurized air and shaft power output a compressor exit bleed port is provided. For portions of the operating spectrum, these engines may be required to dump bleed air into the engine exhaust to maintain the compressor-turbine flow match, and suffer penalties in performance.

In addition to the parametric APU cycle study, then, Task II included an evaluation of engine and component configuration changes consistent with each level of technology, seeking to define alternative configurations which would have a favorable impact on APU performance and weight.

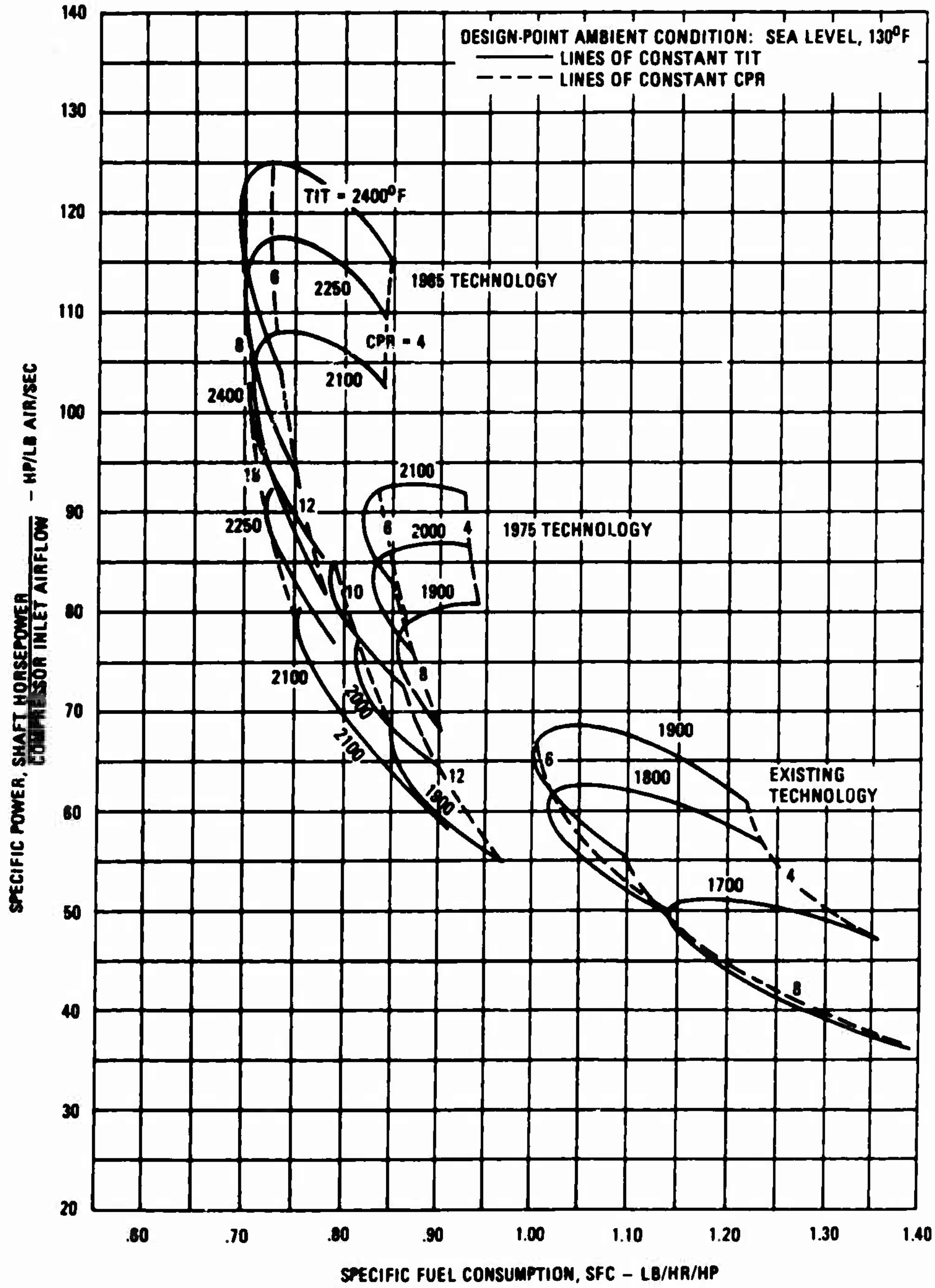



Figure 18. Design-Point Shaft-Power Performance of Simple-Cycle Parametric APU Engines.

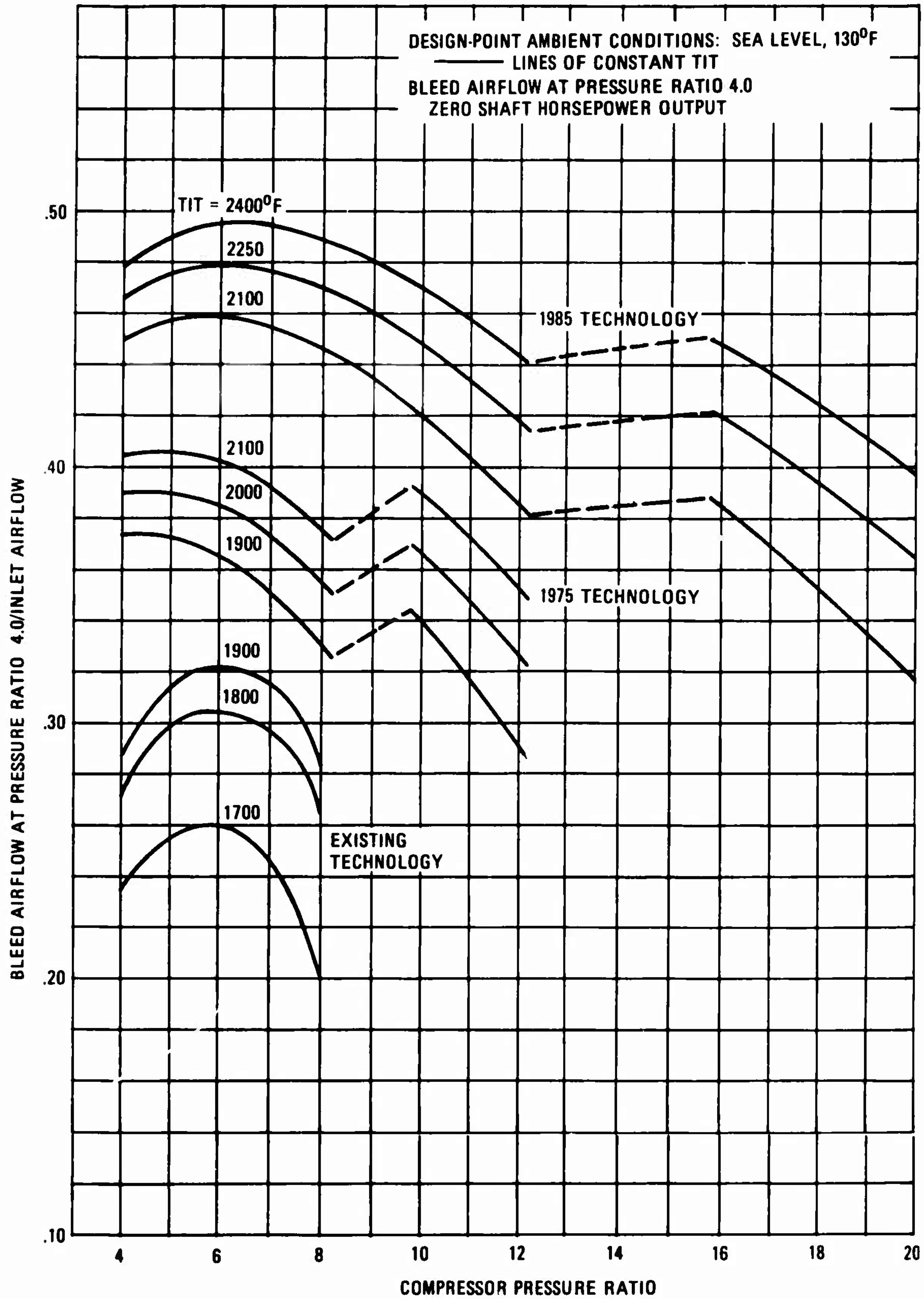



Figure 19. Design-Point Bleed-Air Performance of Simple-Cycle Parametric APU Engines.

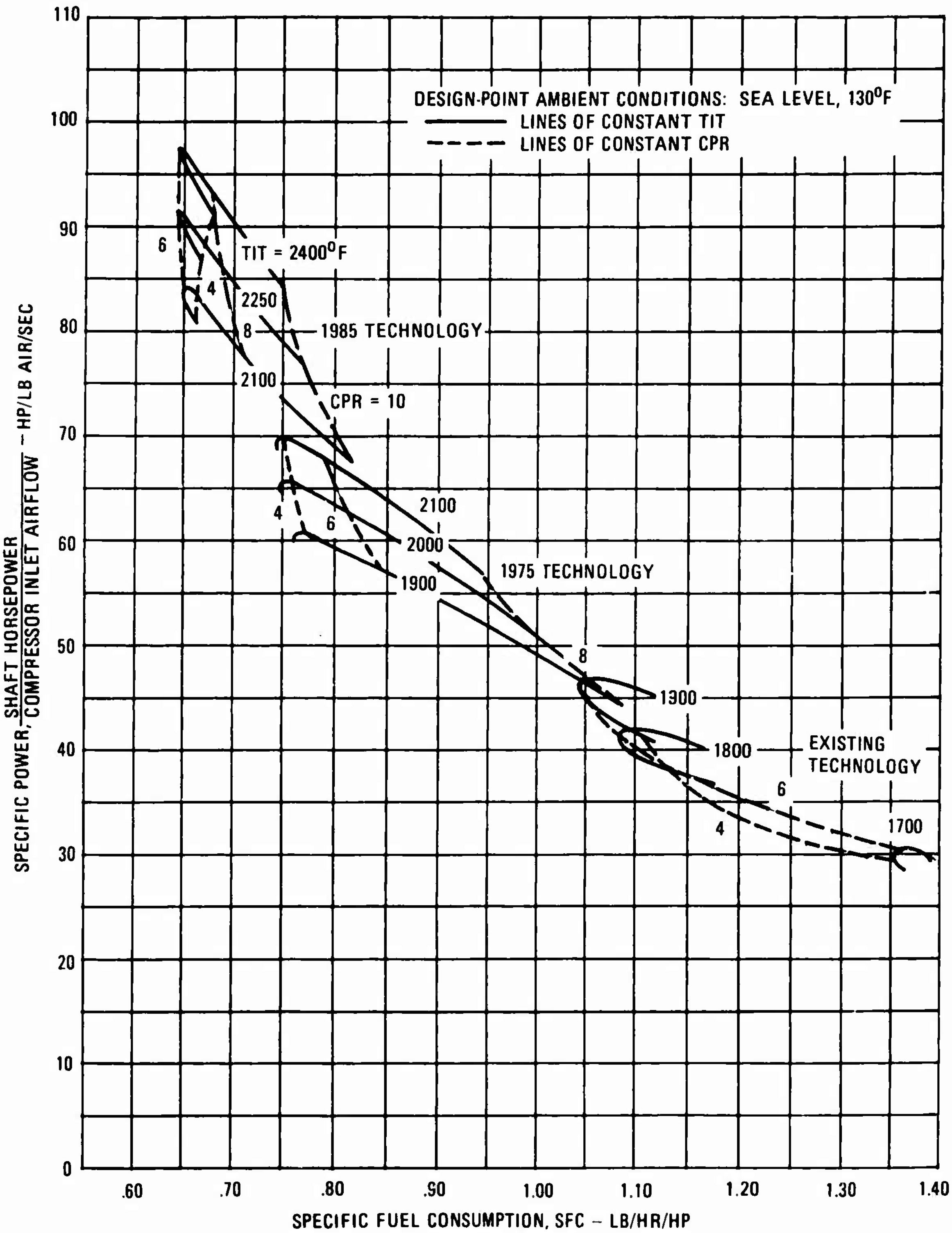



Figure 20. Design-Point Shaft-Power Performance of Regenerative Parametric APU Engines (0.60 Effectiveness).

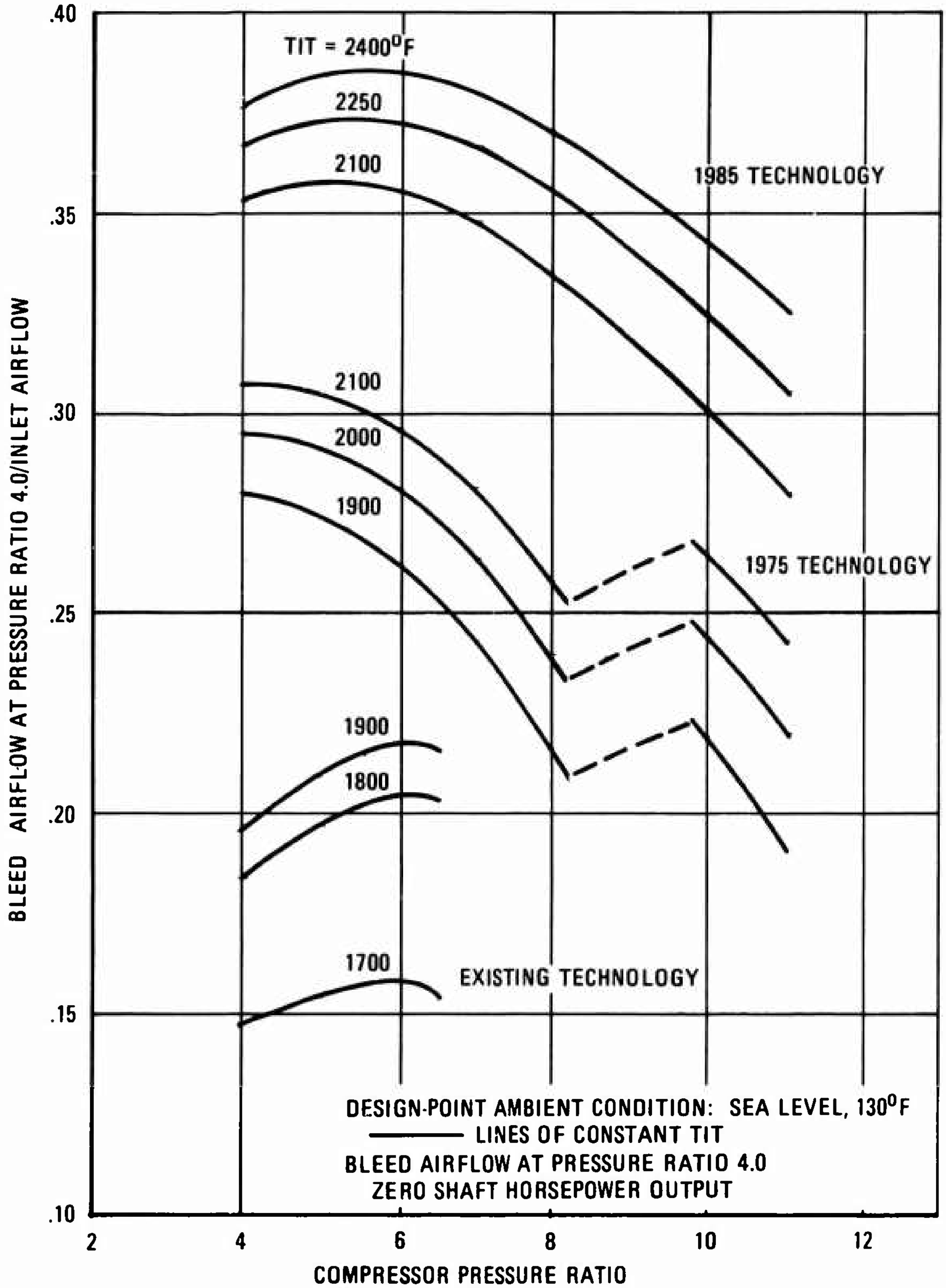



Figure 21. Design-Point Bleed-Air Performance of Regenerative Parametric APU Engines (0.60 Effectiveness).

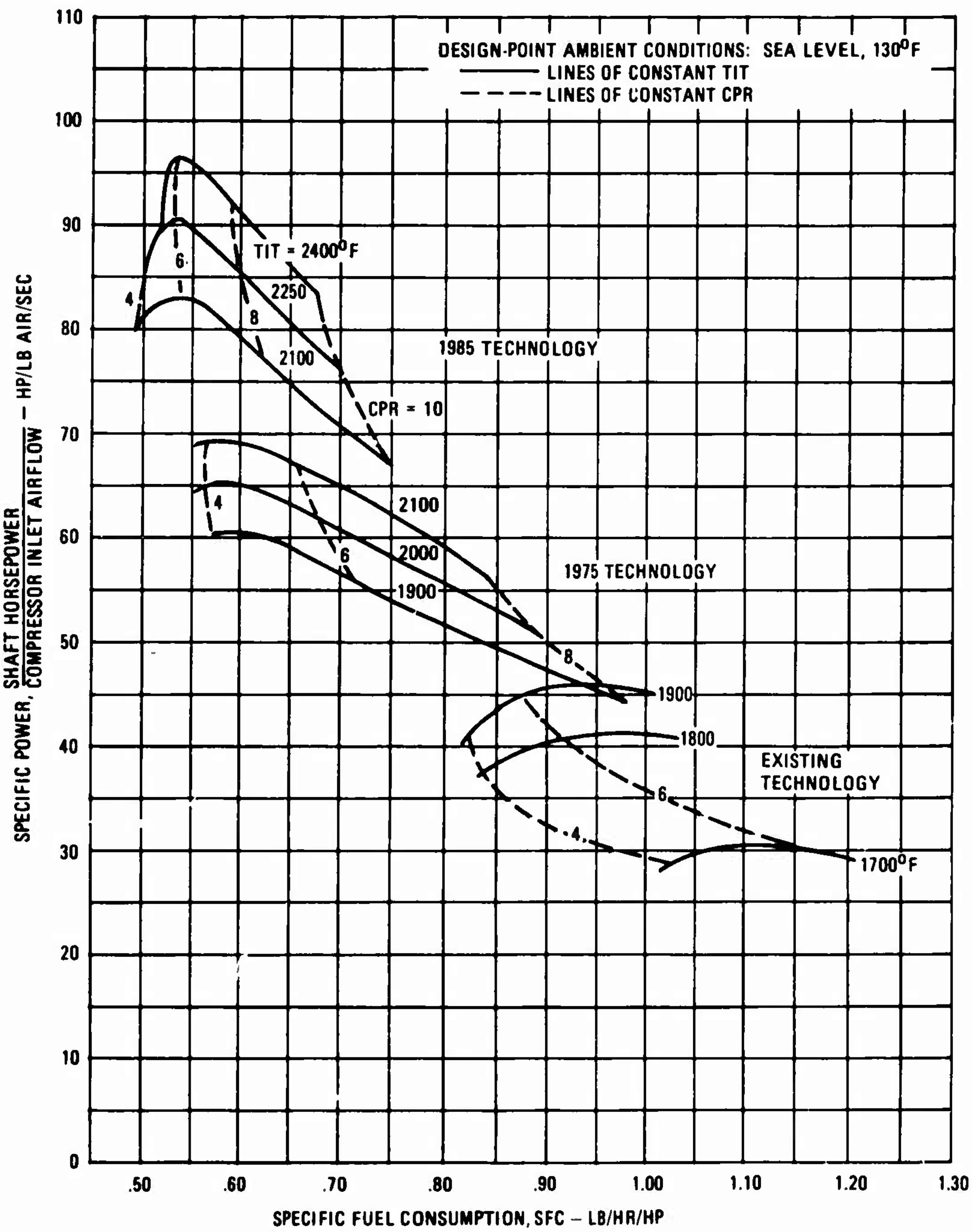



Figure 22. Design-Point Shaft-Power Performance of Regenerative Parametric APU Engines (0.90 Effectiveness).

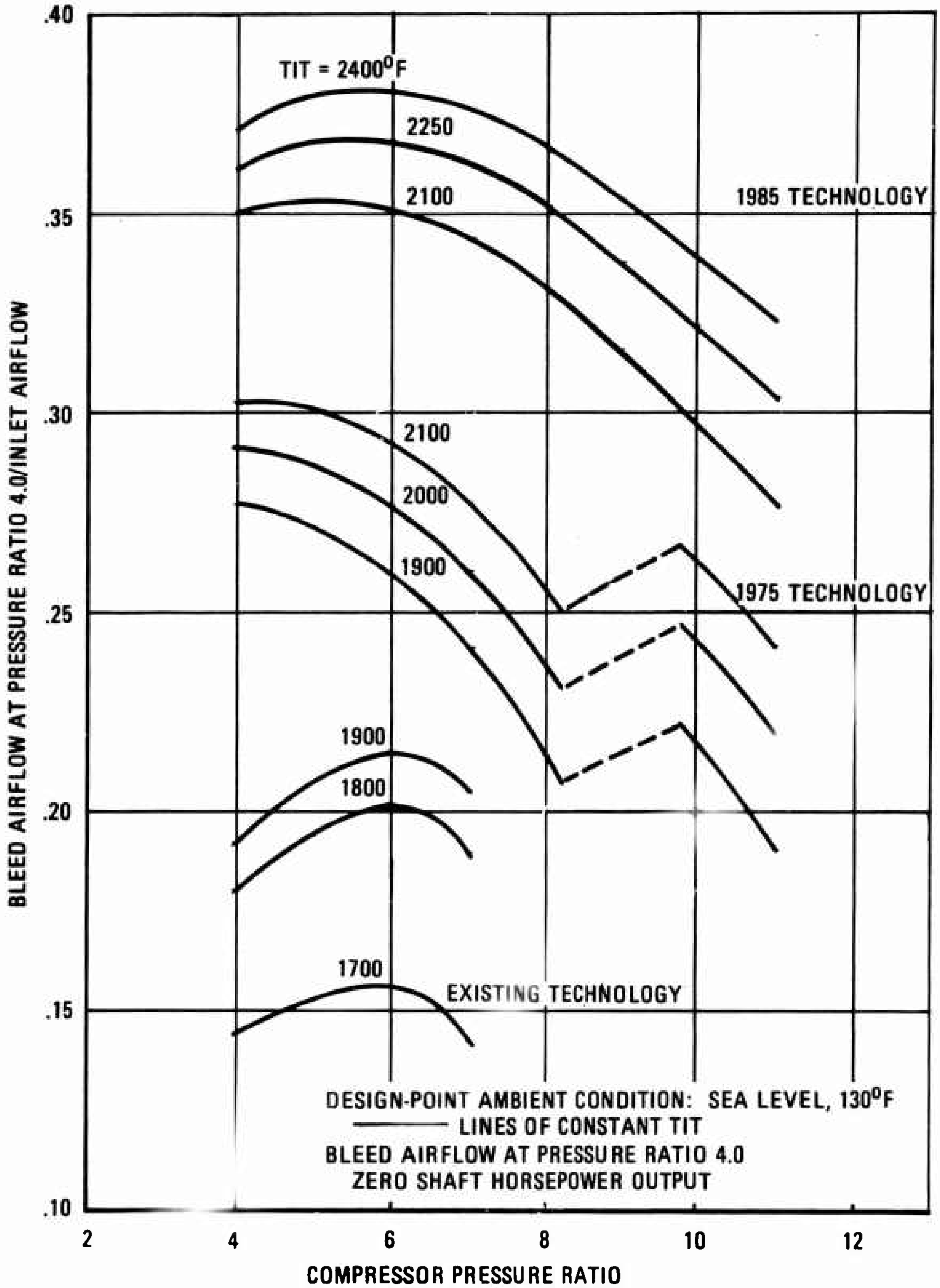



Figure 23. Design-Point Bleed-Air Performance of Regenerative Parametric APU Engines (0.90 Effectiveness).

Evaluations of the following configuration changes and the potential trade-offs in APU performance and weight were investigated:

1. Bleed-APU and engine-driven load compressor (EDC)

2. Single-shaft engine and free power turbine

3. Variable compressor geometry

4. Variable turbine geometry

Also, a trade-off study was performed to determine the optimum regenerator effectiveness applicable to each level of technology and the number of hours of APU operation during the aircraft mission to justify regeneration.

Bleed-APU, Load Compressor

EDC weight and power trends from Reference 1 were used to perform this trade-off study, in comparison with a baseline of bleed-APU data. Weight and power curves from Figure 55 of the reference, converted to ambient temperature conditions of 130$^{o}$F and plotted in Figure 24 were the basis of the trade-off study. The influence of small differences in mechanical and gearbox efficiencies should result in almost negligible differences in ESFC between bleed-APU's and EDC's. The study did point out the definite weight penalty associated with the EDC. However, the EDC would have superior performance for certain part-power operating conditions in comparison with a simple bleed-APU.

Single-Shaft Engine, Free Power Turbine

The free-turbine engine, at optimum power turbine speed, offered a definite performance advantage at part-power operation when compared with the single-shaft engine. The extent of this part-power performance improvement was strongly influenced by component efficiencies, particularly the compressor performance trends. The performance comparisons for single-shaft versus free-turbine engine were plotted in Figure 25.

At constant output-shaft speed, this picture would be considerably different. A free power turbine, with the shaft speed optimized at the design point, would have higher part-power fuel flows. Conversely, a free power turbine, with the output-shaft speed optimized at some part-power point, would have higher fuel flows at all other operating conditions - including the design-point. If extensive operation of the engine at some part-power condition were anticipated, the power turbine could be designed so that the optimum turbine speed would coincide with the constant output shaft speed at that condition,

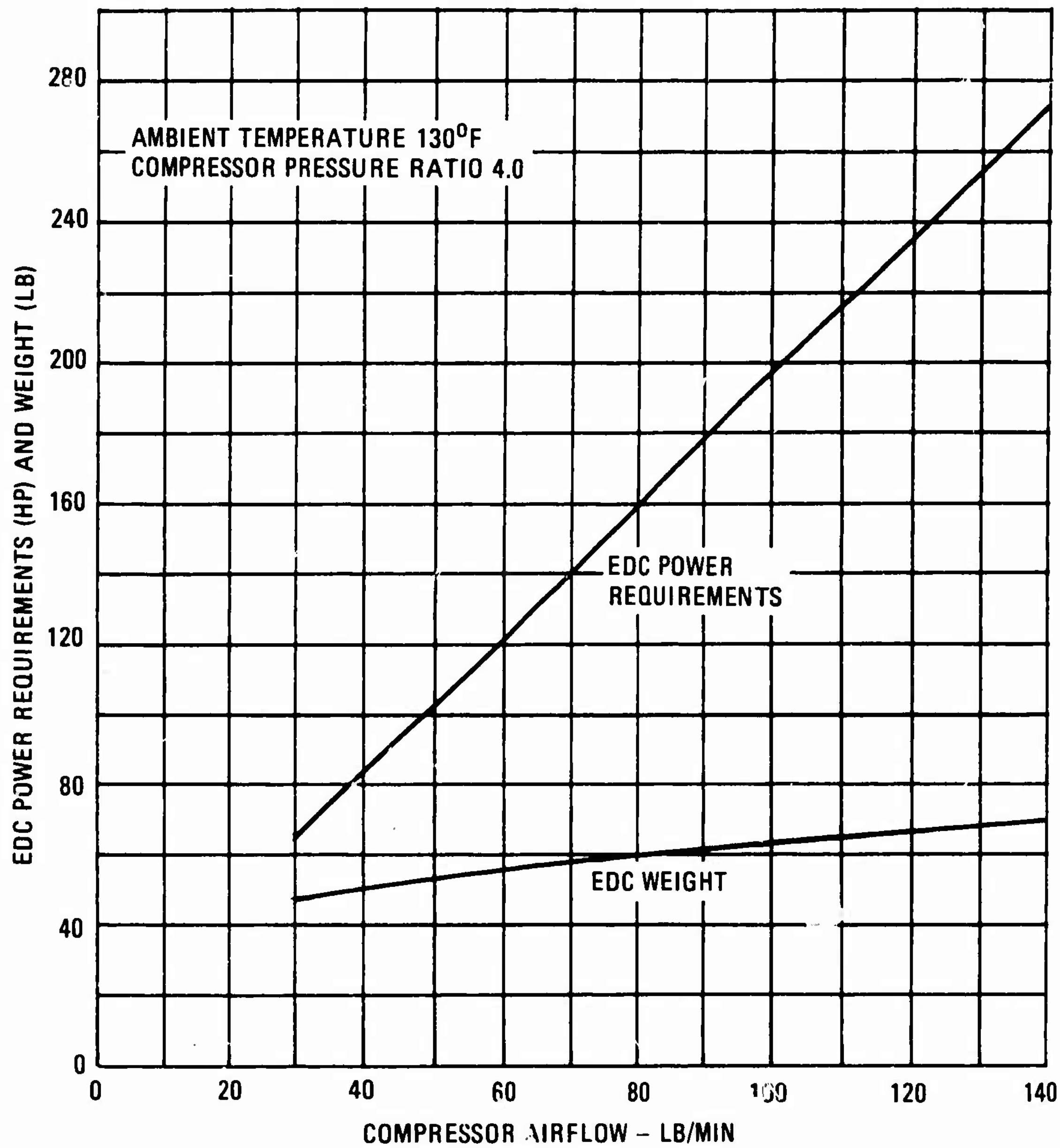



Figure 24. Weight and Power Requirements of Engine-Driven Load Compressors, EDC (Reference 1).

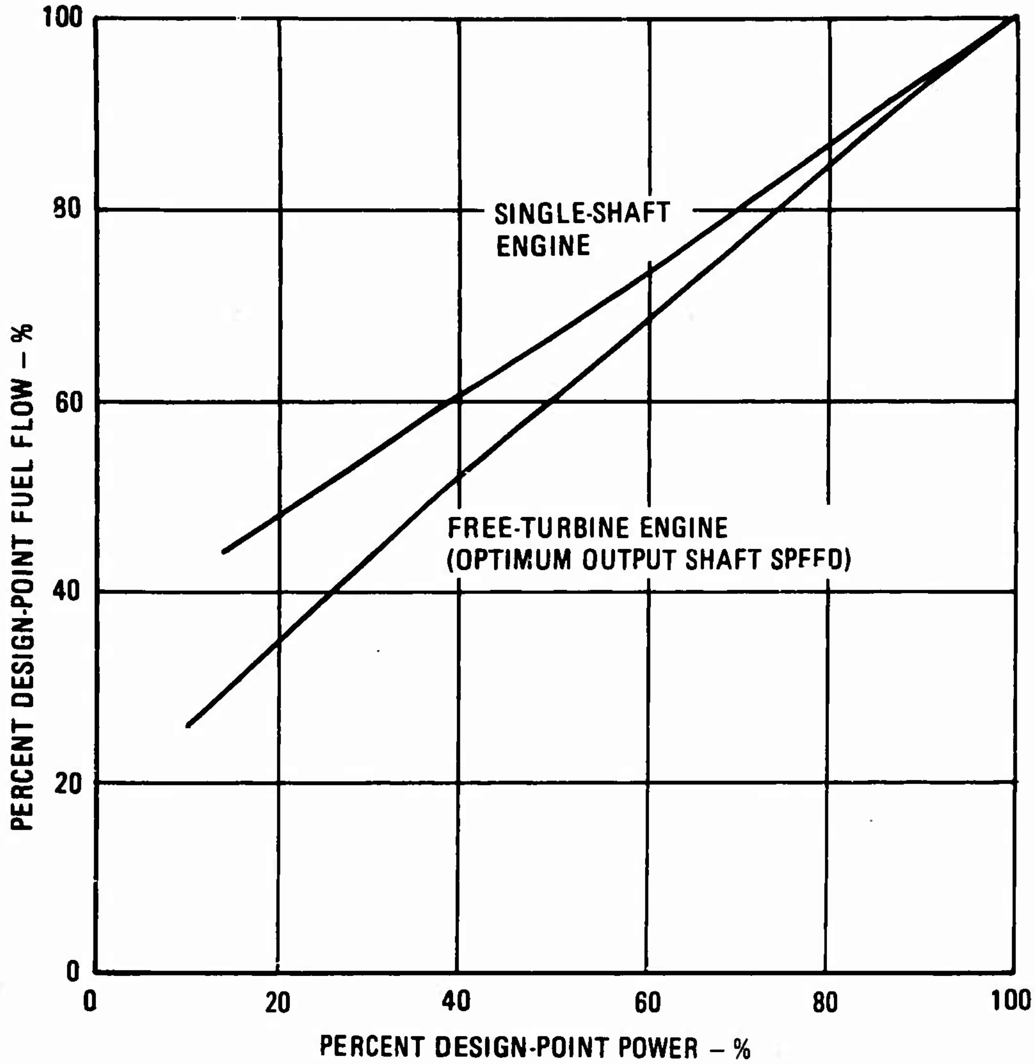



Figure 25. Part-Power Performance of Single-Shaft and Free-Power-Turbine Engines.

and the performance of the engine would be compromised at higher power operating points.

The disadvantages of the free-turbine engine are the added complexity of an additional shaft and bearings and, consequently, higher weight, in addition to added complexity in the fuel control. However, starting torque requirements would be reduced, the requirement for a clutch would be obviated, and weight savings could be realized in the APU starter.

## Variable Compressor (Turbine) Geometry

Bleed-APU's of present technology are single-shaft machines which provide shaft-power output and compressor-exit bleed airflow. These bleed machines perform poorly when, during certain aircraft operating modes which call for shaft power and minimum bleed, some compressor air must be dumped directly into the engine exhaust to maintain compressor-turbine flow matching. One solution which offers improved performance would be a free-turbine engine with an EDC. Another solution would be variable diffuser vanes in an advanced-technology compressor, matching the requirements of various operating modes by providing variable airflow capability from the compressor at constant pressure and temperature. The compressor should have a wide flow range to exploit to the fullest extent the advantages such a configuration affords.

The performance of a low-pressure-ratio, single-shaft bleed-APU was compared with that of a bleed-APU incorporating variable compressor diffuser geometry in Figure 26. The variable-geometry engine had a flatter ESFC characteristic at part-power conditions.

The further improvement to ESFC that could be achieved with variable turbine geometry was so slight - unless variable turbines are employed in conjunction with a regenerator - that the added complexity and weight would overshadow the reduction in ESFC.

## Regeneration

The addition of a heat exchanger generally improves the thermal efficiency of an engine, and reduces the SFC, by recovering part of the heat energy exhausted from the turbine, transferring it to the compressor exit airflow, and reducing the amount of fuel required to achieve the desired turbine-inlet temperature. This gain in SFC is necessarily accompanied by a decrease in specific power, at a given turbine-inlet temperature, because of the pressure losses and leakage associated with the heat exchanger headers and core. At low turbine-inlet temperatures and low values of design effectiveness, these losses may offset

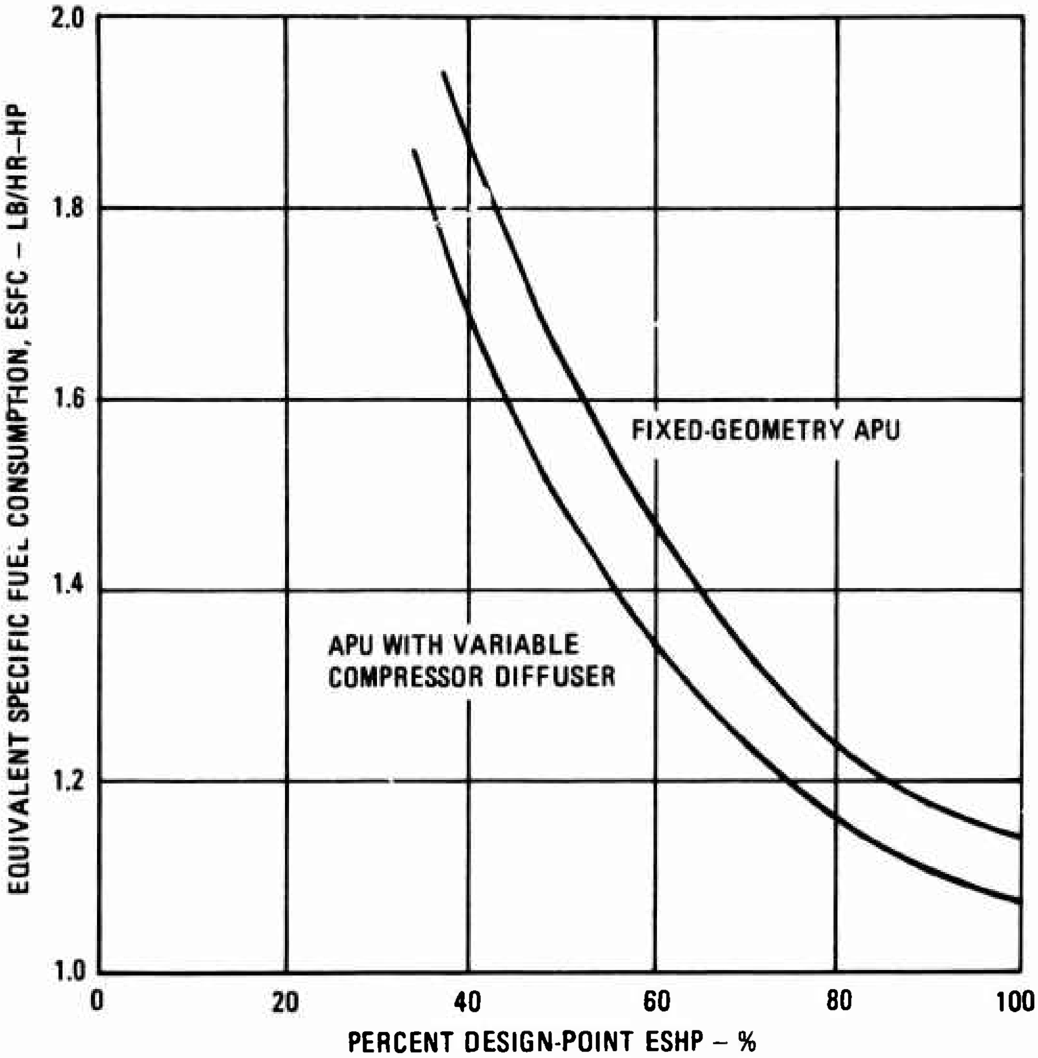



Figure 26. Performance Comparison of Single-Shaft APU With Variable Compressor Diffuser and Fixed-Geometry APU.

the potential improvements due to heat transfer. So the performance of the regenerative engine benefits from high turbine-inlet temperature, which results in high turbine-exhaust temperature, greater difference between compressor-exit temperature and turbine-exhaust temperature, and greater benefit from a given effectiveness regenerator. Although the SFC of the regenerative engine generally improves with increasing turbine temperature, the optimum compressor pressure ratio is relatively low. Increasing the pressure ratio beyond this optimum value increases the compressor-exit temperature and decreases the turbine-exhaust temperature, and the resulting decrease in the benefits accrued from regeneration more than offset the SFC improvement usually associated with higher pressure ratios.

The results of the parametric APU cycle study illustrated that, at the low turbine-inlet temperatures of the existing technology engines, only the effectiveness of 0.90 was sufficiently high to offset the performance penalties resulting from leakage and pressure drops. At the higher turbine temperatures of the 1975- and 1985-technology APU engines, the potential SFC improvements from regeneration increased as effectiveness increased from 0.60 to 0.90. However, the higher value of effectiveness is synonymous with a larger regenerator and increased regenerator weight; Figure 27 presents data from Reference 2 which shows the increasing regenerator specific weight (weight of regenerator for each pound per second of airflow) as a function of effectiveness.

As regenerator effectiveness increases, the improvement in SFC and reduced fuel flow, opposed by the corresponding increase in regenerative engine weight, results in an optimum value of effectiveness for each technology level APU. A trade-off study was performed to determine the optimum effectiveness applicable to each level of technology and the number of hours of APU operation to achieve a fuel flow saving equal to the added regenerator weight. The results for the 1985-technology engine, with the highest turbine-inlet temperature of 2250$^{\circ}$F, were an optimum effectiveness of 0.70 but almost 3-1/2 hours of APU operation for fuel savings equal to regenerator weight.

## APU SELECTION

The results of the parametric APU cycle study led to the selection of APU characteristics applicable to each technology level as shown in Table VII.

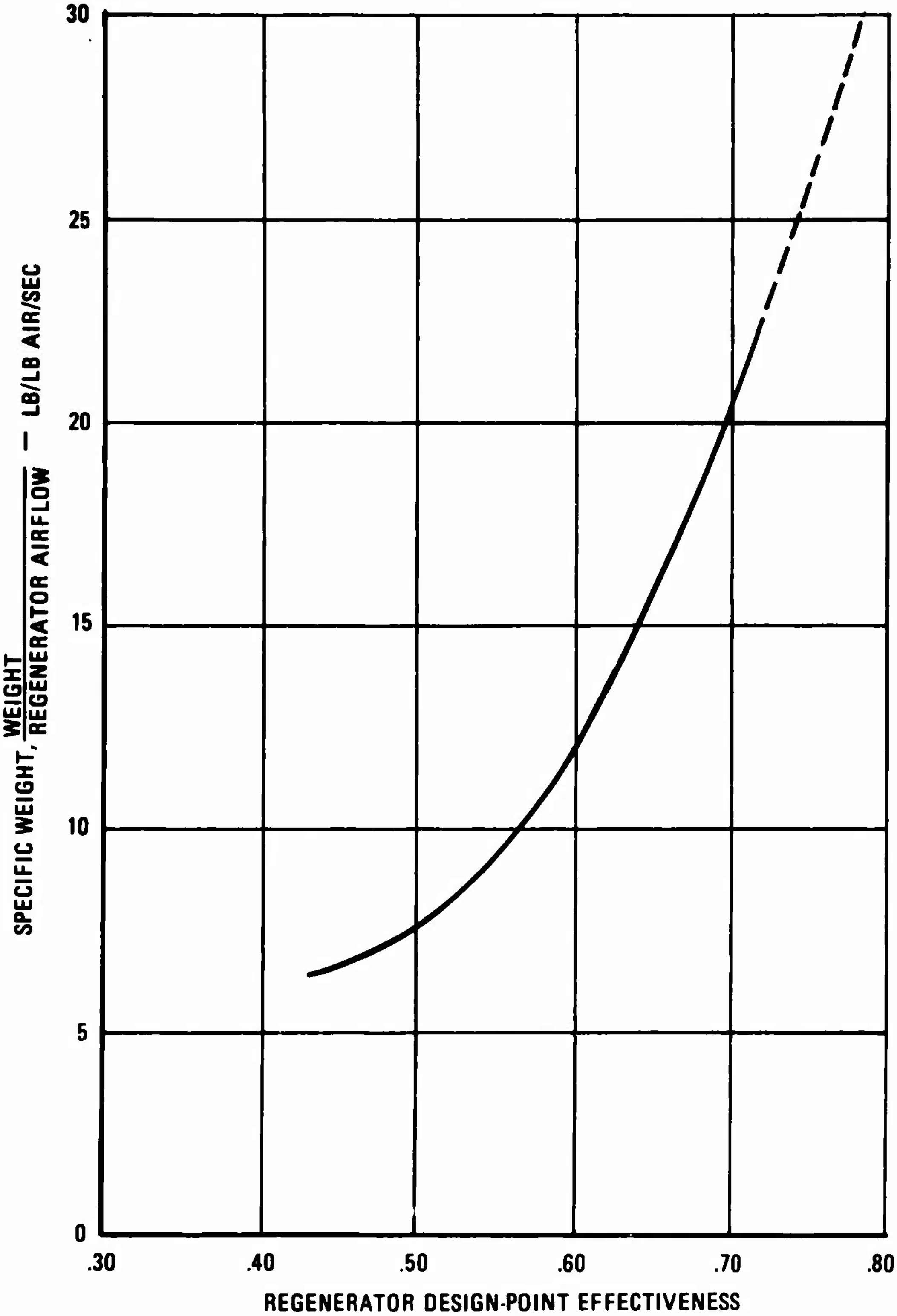



Figure 27. Regenerator Specific Weight - Weight for Each Pound per Second of Airflow (Reference 2).

| TABLE VII. PARAMETRIC APU CYCLE STUDY CONCLUSIONS (AMBIENT CONDITION: SEA LEVEL, 130°F) | | | |
|---|---|---|---|
| Level of Technology | Present | 1975 | 1985 |
| Compressor Pressure Ratio | 4:1 | 6:1 | 8:1 |
| Turbine-Inlet Temperature, °F | 1800. | 2000. | 2250. |
| Specific Horsepower, hp/lb/sec | 56.8 | 85.9 | 114.0 |
| Specific Fuel Consumption, lb/hr/hp | 1.233 | .847 | .699 |

Improvements in part-power performance and starting characteristics with the free power turbine, compared with a single-shaft machine, suggest that this configuration should be considered carefully for advanced APU engines. Also, the high turbine temperatures of the 1985-technology machines offered enough potential improvement in engine performance with a regenerator to warrant investigation of the regenerative configuration, despite its added complexity.

## SECONDARY POWER SYSTEM FUNCTIONS, EVALUATION, AND PRELIMINARY DESIGN

The baseline secondary power system consisted of the power producing components, which include the APU, APU starting system, accessory gearbox (AGB) and driven accessories (hydraulic pumps, electric generators, etc.), main-engine starting, cabin heating and ventilation, and avionics cooling, plus the power distribution system to interconnect these components. Four options of the SPS were defined to include the various possible combinations of the baseline plus cockpit environmental control system (ECS) and/or main-engine starting with an inoperable APU:

1. Baseline (excluding cockpit ECS and main-engine start capability with an inoperable APU)
2. Baseline plus cockpit ECS, excluding main-engine start capability with an inoperable APU
3. Baseline plus main-engine start capability with an inoperable APU, without cockpit ECS
4. Baseline plus cockpit ECS and main-engine start capability with an inoperable APU.

### FUNCTIONS

The following ground rules were postulated in developing the aircraft system functions which require secondary power:

1. It shall be possible to check SPS operation with the aircraft rotor stationary.
2. Fly-by-wire flight control shall not be used.
3. Flight hydraulic power shall be supplied by two 1500-psi pumps, each of 3-gpm capacity.
4. Aircraft rotor rpm during flight will be within a sufficiently narrow range to permit the use of AC generators without constant-speed drives.

Load analyses for the aircraft systems which utilize secondary power - electrical, hydraulic, ECS, and cabin heating and ventilating - are defined in Appendix II. The results of the load analyses have been summarized in Table VIII, which establishes the required APU size.

TABLE VIII. AIRCRAFT SPS REQUIREMENTS AND MODES OF OPERATION

| Operating Mode | Ambient Temp. ($^{o}F$) | Bleed Airflow (P/P=4:1) (lb/min) | Electrical Load KVA | Hydraulic Load (gpm/psi) | Equivalent Shaft Power (hp) | Time Per Mission |
|---|---|---|---|---|---|---|
| *Checkout | $130^{o}$ | 20 | 5 | 1.8/1500 | 66 | 10 Min |
| Engine Start | $130^{o}$ | 20 | 5 | 1.8/1500 | 66 | 30 Sec |
| Max Continuous Inflight Power | Below $35^{o}$ | 20 | 24.7 | 1.8/1500 | 94 | Mission Duration |
| Emergency Inflight Power | $-65^{o}$ to $130^{o}$ | 20 | 1.0 | 0/1500 | 1.7 | Autorotation |

*APU SIZING CONDITION

## Inflight APU Operation

A trade-off study was conducted to determine the relative merits of operating the APU in flight as well as on the ground versus ground operation only. The two modes of SPS operation were evaluated on the basis of eleven parameters. For the trade-off study, these parameters were divided into three groups - a weight group, a cost group, and a safety/reliability group - which were assumed to be of approximately equal importance in evaluating the two options. Accordingly, the eleven parameters which formed the basis of the evaluation were separated into their respective groups, and were assigned weighting factors which were a measure of their relative importance and which also preserved approximately the desired equality of the weight, cost, and safety/reliability groups (Table IX). The mode of SPS operation would have an impact on aircraft complexity in terms of both weight and cost, and so the weighting factor for influence on aircraft complexity was divided equally between the weight and cost groups.

The results of the comparison of APU operation in flight as well as on the ground operation only are presented in Table X. Where the parameters could be quantified, the weighted ratings of the two options are directly related to the values of the parameters. In other cases, the weighted ratings reflect a judgment of the relative goodness of one option compared with another. It was determined that in-flight APU operation was not warranted because of additional weight, complexity of controls, and higher aircraft operating cost, and also the APU was not essential for emergency power in flight.

## CANDIDATE COMPONENTS AND EVALUATION

Gross numbers of possible methods for performing the SPS functions, and the required system components, were compiled initially. Table XI lists the functional elements from which SPS configurations could be synthesized. Some of the elements were eliminated because they were clearly less suitable than others for the proposed application. In other cases, detailed comparative evaluations were made for selection. Following is a description of the selection process used to eliminate certain functional elements and to determine candidate SPS configurations. Column numbers refer to columns of Table XI.

TABLE IX. WEIGHTING FACTORS FOR EVALUATION OF APU OPERATION

| | Weighting Factor | Summation |
|---|---|---|
| <u>Weight Group</u> | | |
| SPS Weight | 13 | |
| Influence on Aircraft TOGW | 13 | |
| 1/2 of Influence on Aircraft Complexity | 4 | |
| SPS Volume | 4 | |
| Sum of Weight Group | | 34 |
| <u>Cost Group</u> | | |
| SPS Life Cycle Cost | 12 | |
| Influence on Aircraft Range | 10 | |
| SPS Maintainability | 8 | |
| 1/2 of Influence on Aircraft Complexity | 4 | |
| Sum of Cost Group | | 34 |
| <u>Safety/Reliability Group</u> | | |
| SPS Reliability | 10 | |
| Emergency Use | 10 | |
| SPS Complexity | 8 | |
| SPS Vulnerability | 4 | |
| Sum of Safety/Reliability Group | | 32 |
| TOTAL | | 100 |

TABLE X . APU GROUND AND FLIGHT CAPABILITY VERSUS GROUND CAPABILITY ONLY

| Parameter | Weighting Factor | Parameter Value | | Weighted Rating | | Notes |
|---|---|---|---|---|---|---|
| | | Ground Only | Ground and In-Flight | Ground Only | Ground and In-Flight | |
| Weight, lb | 13 | 465 | 499 | 13 | 12.0 | Controls, APU IR Suppressor |
| TOGW, lb | 13 | 1070 | 1280 | 13 | 10.5 | Airframe plus Fuel Weight |
| Life-Cycle Cost | 12 | Baseline | Baseline + 12% | 12 | 10.5 | Based on SPS (not only APU) APU, Controls, IR Suppr., Fire Protection and Fuel Cost Increases |
| Mission Reliability | 10 | - | - | 10 | 10 | No Significant Effect |
| Range Influence, NM | 10 | Baseline (343 NM) | 327 NM | 10 | 9.5 | |
| Emergency Use | 10 | - | Possible Slight Advantage | 9 | 10. | In case of Single-Engine Flight, Could Provide ECS Without Engine Power Penalty |
| SPS Complexity | 8 | - | Slight Increase | 8 | 7. | |
| Maintainability | 8 | - | Slight Increase | 8 | 7. | |
| Effect on A/C Complexity | 8 | - | Slight Increase | 8 | 7. | |
| Volume | 4 | - | Slight Increase | 4 | 3. | |
| Vulnerability | 4 | - | - | 4 | 4. | No Significant Effect |
| Total | 100 | | | 99 | 90.5 | |

TABLE XI. SPS COMPONENT POSSIBILITIES

| 1<br>Engine Start | 2<br>Accessory Transmission Drive | 3<br>APU | 4<br>APU Start | 5<br>Electrical Power Generation | 6<br>Generator Drive | 7<br>Flight Hydraulic Power Generation | 8<br>Pneumatic Power Generation | 9<br>Air Conditioning | 10<br>Heating and Ventilating | 11<br>Engine Start Without APU | 12<br>Emergency SPS |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Hydraulic Motor | Direct Gear Coupling | Single-Shaft, Integral Bleed | DC Motor | AC Generator System | Transmission | Transmission-Driven Pumps | Engine Bleed | Air Cycle | Bleed Air Heater | Cartridge Hydraulic or Pneumatic Starter | Transmission Driven Generator and Pump |
| Motor-Pump | Hydraulic-Driven AGB | Free Turbine, Integral Bleed | Starter-Generator | DC Generator System | Hydraulic Motor | Pneumatic-Driven Pumps | Transmission Driven Compressor | Vapor Cycle | Combustor Heater | Cartridge Power for Impingement Starter | Battery and Inverter |
| ATM | Pneumatic-Driven AGB | Single-Shaft, No Bleed | Hydraulic Motor | | ATM | Electric Motor Pumps | | | Electric Heater | Cartridge Power to Drive APU | Hydrazine-Driven Generator and Pump |
| Electric Motor | Shaft-Driven AGB | Free Turbine, No Bleed | Hydraulic Motor-Pump | | Engine-Driven | Engine-Driven Pumps | | | | Accumulator | APU |
| Starter-Generator | Electric-Motor-Driven AGB | | ATM | | | | | | | Buddy System | |
| Mechanical Link to AGB | | | | | | | | | | | |

Column I - Main-Engine Starting

The motor-pump was eliminated. The pump feature would not be reliable enough to serve as a primary hydraulic source, since it depends upon the engine's being in operation.

The electric motor starter and starter-generator were eliminated. Because of the high power required for starting the main engine, electric starting would entail a relatively large weight penalty. An electric motor starter would weigh approximately 35 pounds. A starter-generator would weigh approximately 50 pounds and would require a regulator control unit weighing 3 to 5 pounds. Input to the starter would reach a peak of 25 kw. At 22v, this would correspond to 1100 amp, requiring unusually heavy wiring and switching. If start capability were desired without assistance from the battery, the APU and APU generator would be penalized by the relatively low efficiency of the electric start chain:

Estimated -

| | | |
|---|---|---|
| Starter Efficiency | = | 60% |
| Transformer-Rectifier Efficiency | = | 80% |
| Generator Efficiency | = | 80% |
| Combined Efficiency | = | 38% at peak load |

Thus for 20 horsepower input to the engine starter pad, an input to the generator of approximately 50 horsepower would be required. By way of contrast, a starting scheme using a hydraulic pump powered by the APU and a hydraulic motor on the engine would have an efficiency of 70%, excluding line losses.

Because of the high current requirement of the DC starter, a special power supply such as a high-capacity transformer-rectifier unit (T-R) would be required to convert AC generator power to DC power. For electric motor starting, the weights of the components in the engine start chain would include 70 pounds for two starter motors, 20 pounds for increased T-R capacity, and 10 pounds for controls and wiring - a total of 100 pounds. By comparison, weights for hydraulic starting would include 19 pounds for two starter motors, 5 pounds for increased pump capacity, and 25 pounds for controls and plumbing - a total of 49 pounds. For 1975 and 1985 time

frames, the T-R weight penalty could be reduced by developing and applying a high-voltage DC starter to operate directly from the rectified output of the AC generator. In this case, a rectifier unit rather than a transformer-rectifier unit would be used, thus saving the weight of the transformer. However, electrical starting would still be appreciably heavier than hydraulic.

Mechanical starting of engines was eliminated because this would be heavier, more complex, and a greater technical risk than hydraulic or pneumatic starting. Mechanical starting refers to shaft-linking of the APU and engine start pad, involving a right-angle gearbox and torque converter/decoupler for each engine - the torque converter to convert APU constant-speed torque to variable-speed input torque to the engine starter pad, and the decoupling to isolate the engine starter pad from the APU, except during starting. The comparable hydraulic starting scheme would use two hydraulic starter motors and one accessory-gearbox-mounted pump. It was estimated that each right angle gearbox, with its bearings and supports, would weigh more than a hydraulic starter, and each torque converter/decoupler would weigh more than the pump-motor of the AGB. An additional weight penalty to the mechanical system could result from restraints on installation design, dictated by the need to achieve suitable mechanical linking of the AGB and engine starter pads.

Main-engine starting with hydraulic motors or pneumatically, with an ATS, was retained for consideration in candidate secondary power systems.

Column 2 - Accessory Transmission Drive

Direct transmission drive, defined as a solid gear coupling so that the flight pumps and generators are driven only by the aircraft rotor transmission, was eliminated. This scheme was not compatible with the ground rule requirements for checkout of all the SPS with the aircraft rotor stationary.

Electric motor drive was eliminated because of relatively high weight and acquisition cost. Comparing estimated component weights and costs for hydraulic and electrical drives for the AGB (present technology), the hydraulic drive would require a pump (5 pounds, $1200) and a motor (4 pounds, $800) - totalling 9 pounds and $2000. The electrical generator (22 pounds, $2800) and motor (18 pounds, $1200) totals 40 pounds and $4000.

Hydraulic-, pneumatic-, and shaft-driven transmission accessory drives were retained as contenders for SPS configurations.

Column 3 - APU

APU's without bleed air supply were eliminated. A pneumatic system was required for ECS, and the discussion of the options offered in Column 8 shows the desirability of a bleed-air APU compared to an engine-driven compressor.

The remaining options were single-shaft and free-turbine APU's with bleed capability. The single-shaft APU mounted directly on the AGB would certainly entail a larger APU starter than a free turbine, because the starter also would have to accelerate all the AGB-mounted equipment. Consequently, an additional option was introduced - a single-shaft, integral bleed APU with a fillable fluid coupling. The fluid coupling would be empty for APU start, removing the AGB load from the engine shaft.

In the final selection, a single-shaft APU without a fluid coupling was selected from among the three candidates. The selection of the APU configuration, as well as its starter concept, is analyzed in detail in the section on APU CONFIGURATION AND APU STARTING.

Column 4 - APU Starting

The hydraulic motor-pump was eliminated except for one case where it is required for AGB drive. In all other cases, the pump function is not required, since the AGB pumps can supply required hydraulic power.

The starter-generator was eliminated because the generator function of the unit was not useful enough to justify it. It is anticipated that several kva of AC load will be required during ground operation and check-out. Using a DC source to serve these loads would require a relatively heavy inverter; for example, a 2.5-kva inverter is estimated to weigh 30 pounds (current technology). For the weight of an inverter and DC-generator voltage regulator, a relatively high capacity AC generator could be provided (a 20-kva generator which weighs 25 pounds is currently available). If the AGB were driven by the main rotor transmission, an APU-mounted AC generator could power any of the aircraft AC and DC electrical loads. However, the direct transmission drive was eliminated previously because it was incompatible with the ground rules; consequently, when the AGB is powered by the APU, there would be no need for the APU generator function since the main generators are on the AGB.

The ATS was eliminated because of the difficulty in providing compressed air. In order to have self-contained starting, it would be necessary to have an on-board compressor to charge the air bottle. Therefore, this approach would be heavier, more costly, and less reliable than a hydraulic starting scheme, where a hydraulic accumulator would be charged by a relatively small and simple hydraulic pump.

The electric motor starter was eliminated as a result of a detailed comparative evaluation described in the section APU CONFIGURATION AND APU STARTING, which shows that hydraulic starting is better suited to this application than electric. Only hydraulic-motor APU starting remained as a candidate for SPS configurations.

Column 5 - Electrical Power Generation

An AC-generator system was preferred over DC because of the relatively large amount of AC load (an electric load analysis is shown in Appendix II). It was proposed to supply the DC load from transformer-rectifier units. An AC-to-DC converter would be relatively simple and lightweight; for example, a 60-amp transformer-rectifier unit is estimated to weigh less than 10 pounds (present technology) and requires no regulation control. Conversely, a DC-generator system would require the provision of DC-to-AC conversion equipment and would result in a large penalty in weight and reliability. A large (2 to 5 kva) inverter is estimated to weigh over 10 pounds per kva (1970 technology). The inverter is a complex unit having both frequency and voltage regulation.

Column 6 - Generator Drive

The transmission-drive generator was selected because this is the most efficient and reliable means for driving the generator.

A hydraulic drive for the generator would involve increased weight, reduced efficiency, and reduced reliability, because of the addition of the hydraulics.

A pneumatic drive for the generator would require speed governing, and it would have to be designed to provide adequate output torque and speed at all engine power conditions in flight. In case of dual engine failure, generator operation would be lost.

Engine-driven generators have two serious drawbacks: engine speed is not maintained within a sufficiently narrow band, and failure of an engine causes loss of output for the generator.

Column 7 - Flight Hydraulic Power Generation

A transmission drive was selected because this would be the most efficient and reliable means for driving the hydraulic pumps.

Pneumatic or electrical drives for the pumps would result in increased weight, reduced efficiency, and reduced reliability, because of the addition of the pneumatic or electrical components.

Engine drive would not be reliable enough to serve as the source of flight hydraulic power, because the pump function would depend on the engine's being in operation.

Column 8 - Pneumatic Power Generation

Engine bleed would be recommended rather than a transmission-driven compressor, because the addition of the compressor would result in increased weight, acquisition cost, and operating cost. The compressor would have to be designed to withstand the torsional vibration and acceleration generated by the aircraft rotor system, as well as the transmission overspeed that occurs during autorotation.

Engine bleed has the advantage of being available from both the APU and the main engines. There is potentially a minor disadvantage in that the available air supply from the main engines might be marginal under certain flight conditions that call for minimum engine power. This is not considered a serious problem, since the pneumatic system serves only functions that are not flight-critical, and it is assumed that subnormal performance of these loads is acceptable for short periods.

Column 9 - Air Conditioning

An air-cycle unit was selected, rather than a vapor-cycle type, because of weight and reliability considerations.

Column 10 - Heating and Ventilating

Bleed-air heating was recommended because of weight and reliability considerations.

A combustion heater would have the disadvantage of relatively high complexity, because of the requirements for a fuel control and fire detection. Also, the combustion air intake and exhaust provisions could result in appreciable weight increase, depending upon where the unit is installed.

An electrical heater would have the disadvantage of adding a large electrical load at a time when overall electric load is at a peak, because of blade de-icing and windshield heating. Cabin electric heating would tend to increase the size of the electrical power system.

Column 11 - Engine Starting Without APU

If engine starting with an inoperable APU is required, it is recommended that a cartridge-pneumatic starter be substituted for the pneumatic starter or that a cartridge-powered hydraulic pump be added for hydraulic engine starting.

An impingement starter, with cartridge-supplied high-pressure air impinging directly on the gas producer rotor blades to accelerate the gas producer during the start cycle, would be a good approach if it were developed. It is believed that any advantage that this might have over the cartridge starter is insufficient to justify the cost of developing it. However, if and when it is developed by the engine manufacturer, the impingement starter could be considered in lieu of the cartridge starter.

Cartridge power could be used to drive the APU; however, the APU could fail in a manner that would prevent it from being driven. This approach also had the disadvantage that a relatively large amount of cartridge power would be required, because of losses in the APU and APU-driven components.

An accumulator for main-engine starting would be impractical because of its weight, which was estimated to exceed 200 pounds.

A buddy system was considered to be inadequate to satisfy a requirement for engine starting with an inoperable APU, because it depends on the availability of another aircraft and suitable interconnection equipment. However, if desired, buddy system provisions could be added as an optional backup feature. This would be of special interest if the aircraft specification does not include the requirement for engine start with an inoperable APU.

Column 12 - Emergency SPS

All the SPS configurations which could be synthesized from the remaining functional elements would have transmission-driven generators and pumps. These provisions are adequate to supply SPS power in the event of single- or dual-engine failure, since the aircraft rotor and transmission would always be turning during flight.

SPS Configuration Contenders

Table XII shows the SPS functional elements remaining after the above eliminations and selections. Since Columns 3 through 12 are reduced to single items, candidate SPS configurations can be synthesized by taking all combinations of Columns 1 and 2 of Table XII, yielding six configurations having the following combinations of engine start and AGB-drive functional elements:

| Configuration | Engine Start | AGB Link to APU |
|---|---|---|
| A | hydraulic motor | hydraulic |
| B | hydraulic motor | shaft |
| C | ATS | pneumatic |
| D | ATS | shaft |
| E | hydraulic motor | pneumatic |
| F | ATS | hydraulic |

The last two combinations were eliminated because they are hydraulic-pneumatic hybrids, which do not lend themselves to good design practice and satisfactory maintenance/operational cost.

TABLE XII. SPS COMPONENT CONTENDERS

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Engine Start | Accessory Transmission Drive | APU | APU Start | Electrical Power Generation | Generator Drive | Flight Hydraulic Power Generation | Pneumatic Power Generation | Air Conditioning | Heating and Ventilating | Engine Start Without APU | Emergency SPS |
| Hydraulic Motor | Hydraulic-Driven AGB | Single-Shaft, Integral Bleed | Hydraulic Motor | AC Generator System | Transmission | Transmission-Driven Pumps | Engine Bleed | Air Cycle | Bleed Air Heater | Cartridge Hydraulic or Pneumatic Starter | Transmission-Driven Generator and pump |
| ATM | Pneumatic-Driven AGB | | | | | | | | | | |
| | Shaft-Driven AGB | | | | | | | | | | |

## PRELIMINARY DESIGN

Schematic sketches of the four configurations selected for comparative evaluation are shown in Figures 2 and 28 through 30. Inboard profile drawings, showing proposed SPS component locations for configuration C (remote APU) and configuration D (AGB-mounted APU) are shown in Figures 31 and 32. In each system, the AGB can be driven by either the APU or the main rotor transmission, with isolation of the two maintained by overrunning clutches. During flight, the AGB is driven by the aircraft rotor transmission, and when the rotor is stationary, the AGB is driven by the APU. In configurations B and D, the APU is shaft-coupled to the AGB. In configuration A, the AGB is driven by a hydraulic motor which is powered by a pump on the APU. In configuration C, the AGB is driven by an ATM which is powered by APU bleed air.

Configurations C and D each have 1500-psi hydraulic packs, rated at 3-gpm and 5-gpm respectively. The 3-gpm unit serves flight controls only, and the 5-gpm unit serves flight controls and utility hydraulics. Configurations A and B each have two 1500-psi 3-gpm hydraulic packs for flight control power and a third pump for utility hydraulic power. In configuration A, the third pump is a pump-motor unit which drives the AGB when operated as a motor.

Hydraulic motors are used for engine starting in configurations A and B, and air turbine motors are used in C and D. Where engine start with an inoperable APU is provided, it consists of either of the following schemes. For hydraulic engine starting, a cartridge-powered pump unit is used as an emergency source of power. This unit incorporates a cartridge chamber, air turbine motor, and hydraulic pump. For pneumatic engine starting, a cartridge-pneumatic starter is used on one engine in place of solely a pneumatic starter.

## APU CONFIGURATION AND APU STARTING

The remaining APU candidates at this juncture included a single-shaft configuration, a single-shaft configuration with a fluid coupling at the output to diminish the APU-starting load, and a free-turbine machine.

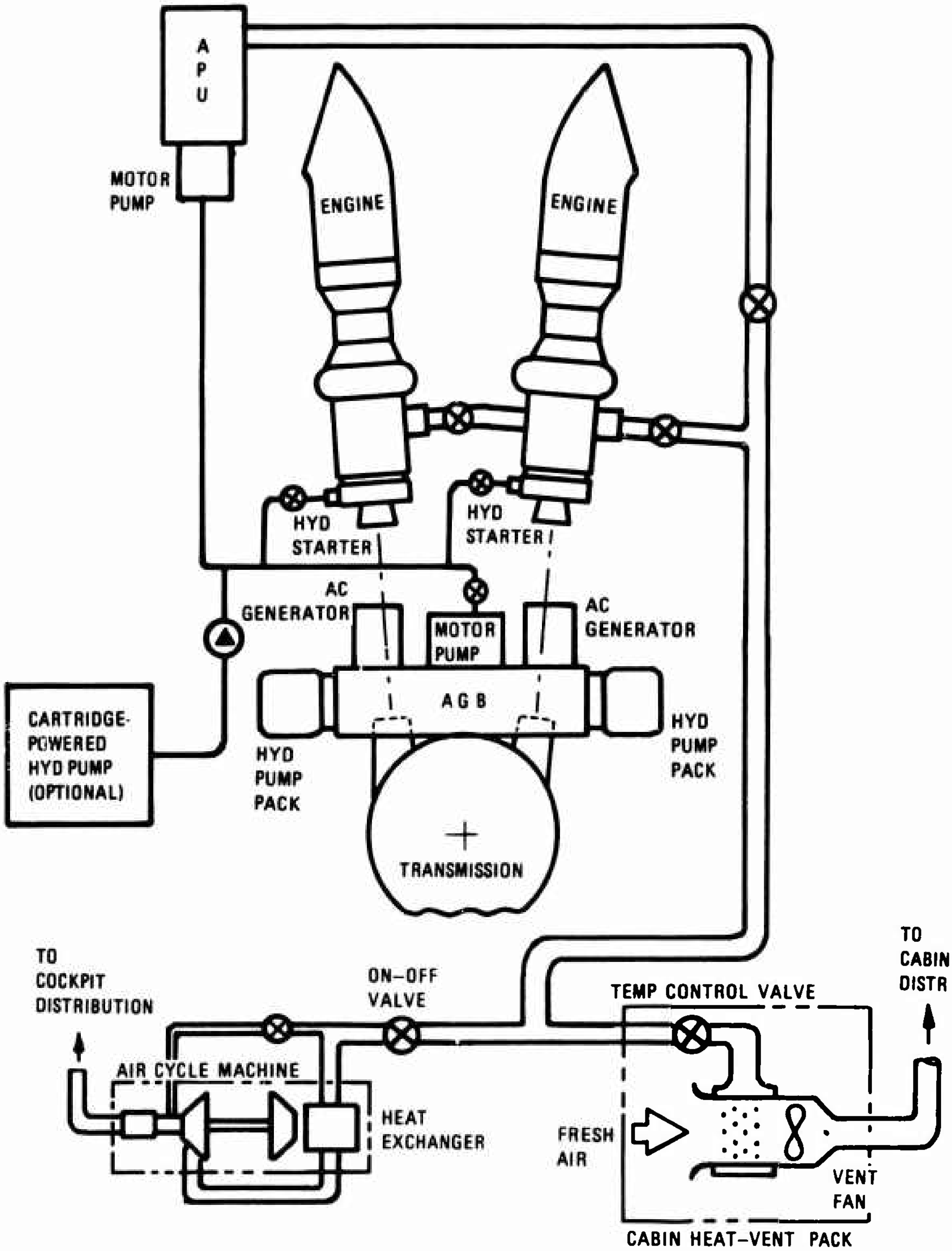



Figure 28. SPS Configuration A - Remote APU, Hydraulic Main-Engine Start, Hydraulic AGB Drive.

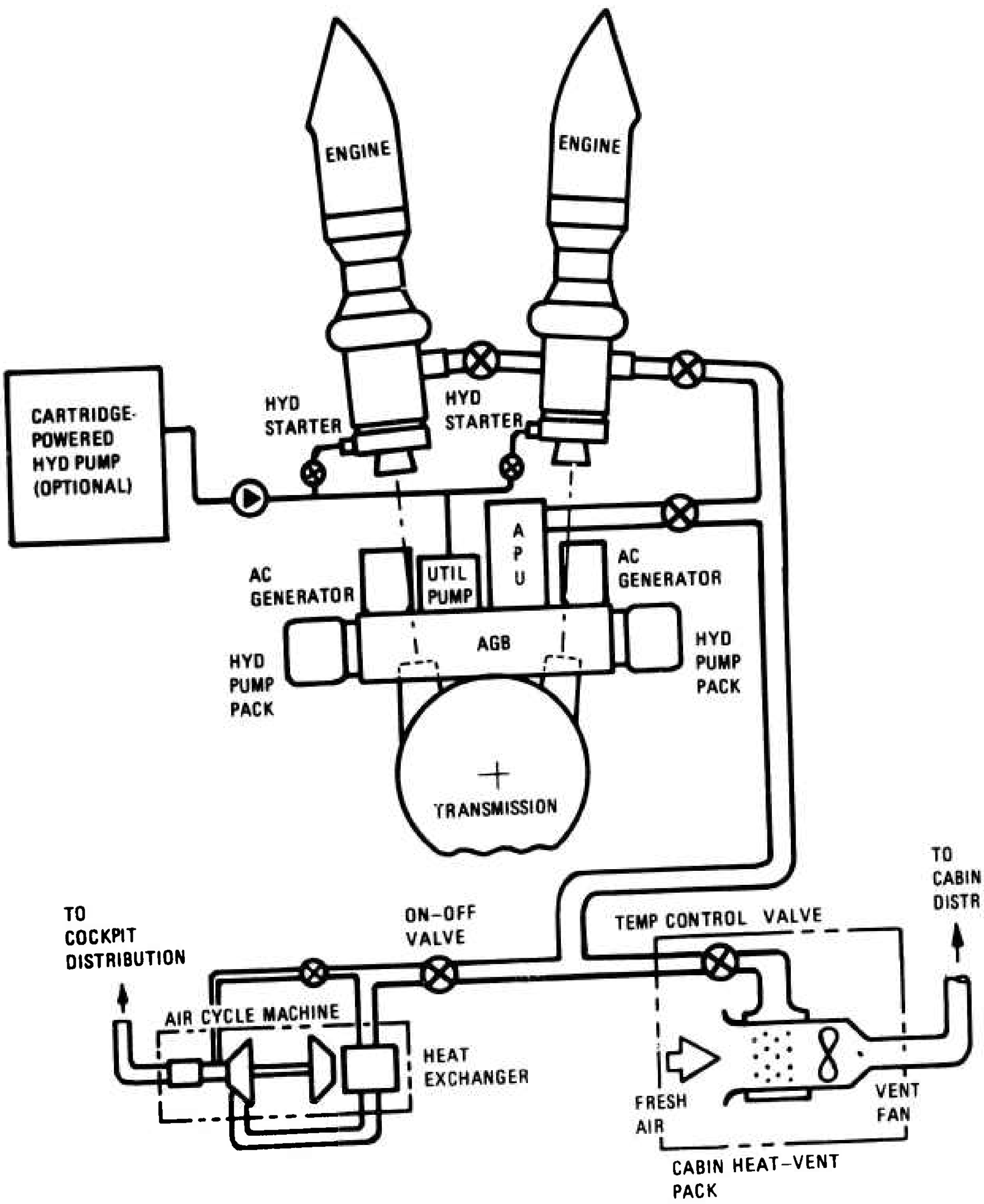



Figure 29. SPS Configuration B - AGB-Mounted APU, Hydraulic Main-Engine Start, Direct-Drive APU.

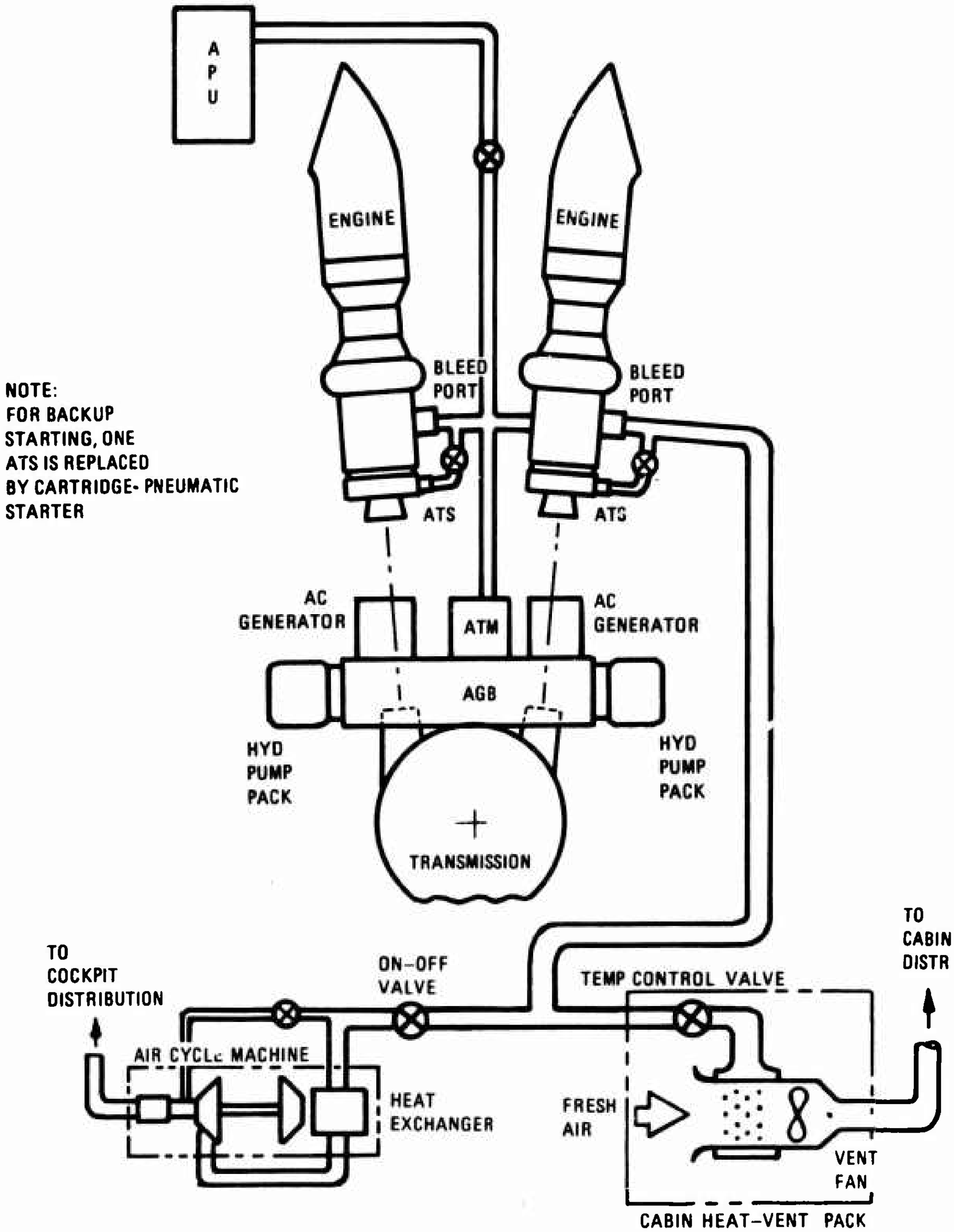



Figure 30. SPS Configuration C - Remote APU, Pneumatic Main-Engine Start, Pneumatic AGB Drive.

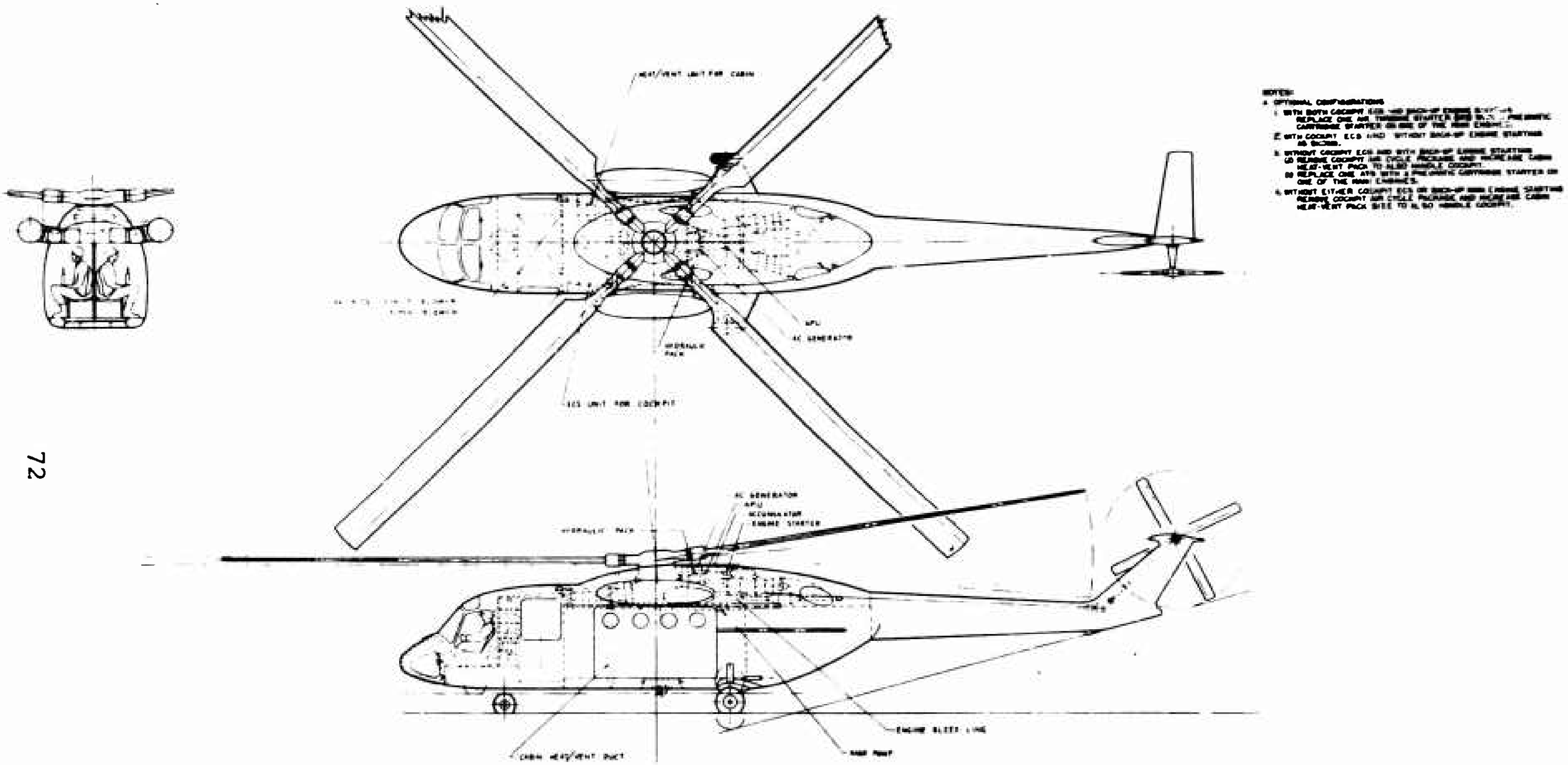


Figure 31. Inboard Profile Drawing of Baseline Helicopter With AGB-Mounted Direct-Drive APU.

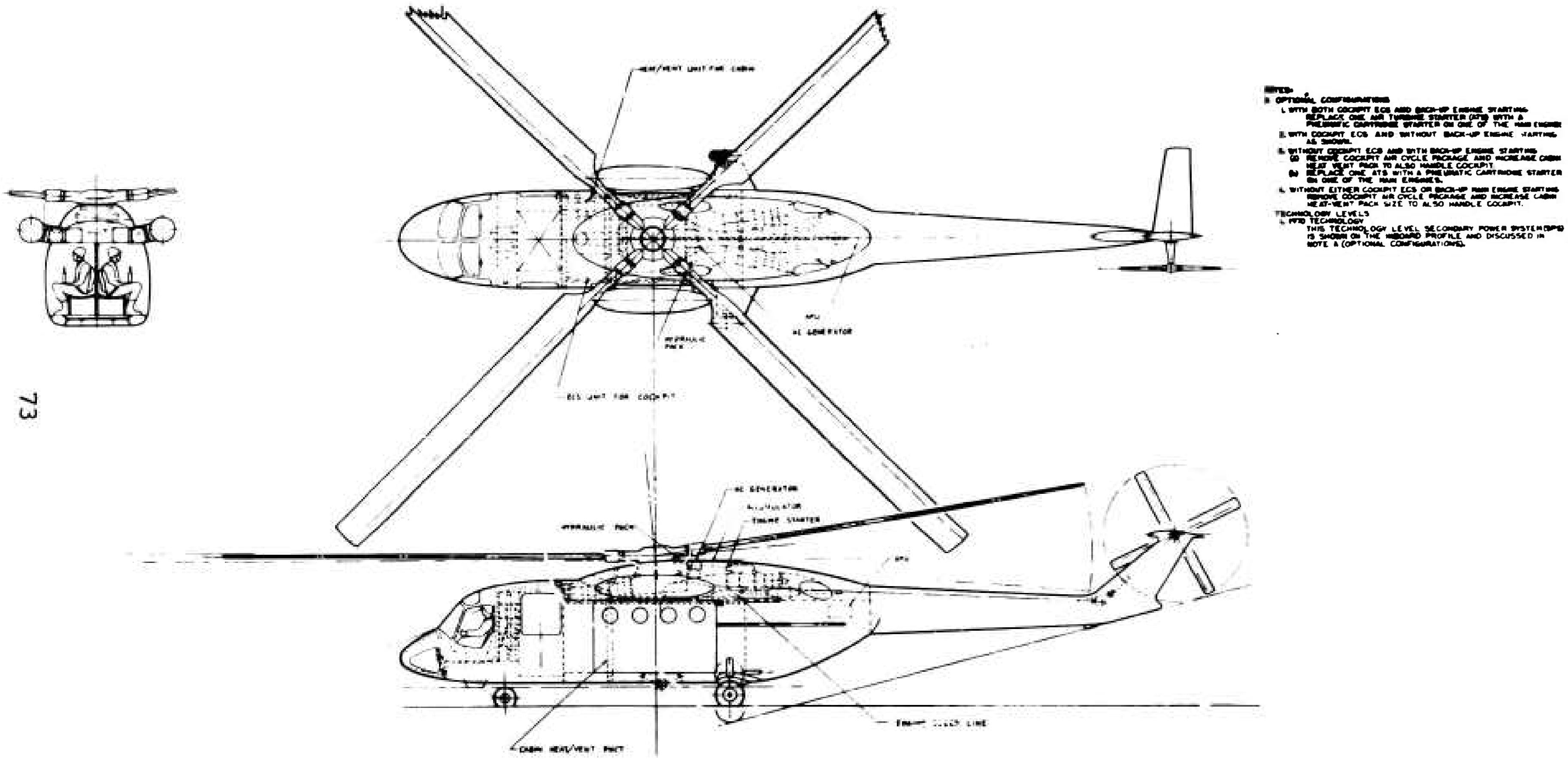



Figure 32. Inboard Profile Drawing of Baseline Helicopter With Remotely Located APU.

The APU's of SPS configurations A and B were required to supply shaft power for hydraulic pumps to provide hydraulic starting of the main engines. The APU's of configurations A, B, and D were required to supply shaft power for AGB drive to support ground checkout, while simultaneously supplying 20 lb/min of bleed air for ECS (or pneumatic main-engine starting in configuration D). The AGB power input requirement for ground checkout was 17 hp - supplying 5 kva of electrical power and 2 hp of hydraulic power. In configuration A, with its hydraulic link between the APU and AGB, inefficiencies in the APU-mounted pump and the AGB-mounted motor plus hydraulic line losses translated into a 26-hp requirement from the APU to produce 17 hp at the AGB. The APU of configuration C supplied only bleed-air power for the SPS, including 20 lb/min for ECS or pneumatic engine starting plus 16 lb/min for pneumatic AGB drive.

To emphasize APU-configuration simplicity, and consequently reliability and minimum cost, all the engines conceived for the SPS had single-stage centrifugal compressors and single-stage radial turbines driving the compressors. The design-point pressure ratios selected for each level of technology as a result of the parametric APU cycle study would be achievable in single-stage radial turbines and compressors, with satisfactory performance and airflow range capability. All the APU's had annular reverse-flow combustors. The shaft bearing support for the single-shaft engines and the gas generator of the free-turbine engine provided an overhung arrangement for compressor and turbine discs with the bearings located in a cool section.

Figure 3 shows schematically the single-shaft APU, with front-drive shaft power output as well as compressor-exit bleed air. The bleed port is located on a scroll collector, which takes air from the diffuser exit. The output shaft speed is reached through a 2-stage spur gear reduction, rather than a planetary train.

Figure 33 shows the bleed-type APU (SPS configuration C), with the starter pad pictured, also. The single-shaft APU with a fluid coupling is represented schematically in Figure 34, which also shows the starter pad for this engine. The hydraulic coupling has a speed-activated lock-in clutch and integral coupling fluid fill system, activated at predetermined engine speed. Finally, the free-turbine APU is pictured in Figure 35. The power turbine is an axial design with a rear drive, exhausting into a scroll collector which surrounds the output gearbox, and a two-stage spur gear reduction reduces the speed of the output shaft.

The free-turbine APU with bleed capability posed severe problems in regard to transient operation of the engine, and required greater complexity in the fuel control and control functions. Rapid changes in bleed flow demand necessitated a power-turbine bypass duct and dump valve; if bleed demand were suddenly reduced, the valve would unload the power turbine and prevent it from overspeeding, dumping the excess engine air into the exhaust collector. Figure 35 illustrates the turbine interstage scroll with diverter dump valve. Then, too, variable power-turbine nozzle geometry would be required to accomplish the necessary excursions in steady-state bleed demand while maintaining constant output speed for the varying power demands.

The APU configuration selection is discussed in detail in Appendix III. Table XIII summarizes the APU performance and weight characteristics for each of the SPS configurations. The requirements of SPS configuration D and the existing (1970) level of technology were used to define a trade-off study among the single-shaft APU, the single-shaft APU with a fluid coupling, and the free-turbine APU. The three candidates were evaluated on the basis of nine parameters, which were divided into three groups assumed to be approximately equal in importance in evaluating the options: a weight group, a cost group, and a safety/reliability group. Accordingly, the nine parameters which formed the basis of the evaluation were separated into their respective groups and were assigned weighting factors which were a measure of their relative importance and which also preserved approximately the desired equality of the weight, cost, and safety/reliability groups (Table XIV). Because the APU would impact on aircraft complexity both in terms of weight and cost, the weighting factor for influence on aircraft complexity was equally divided between the weight group and the cost group.

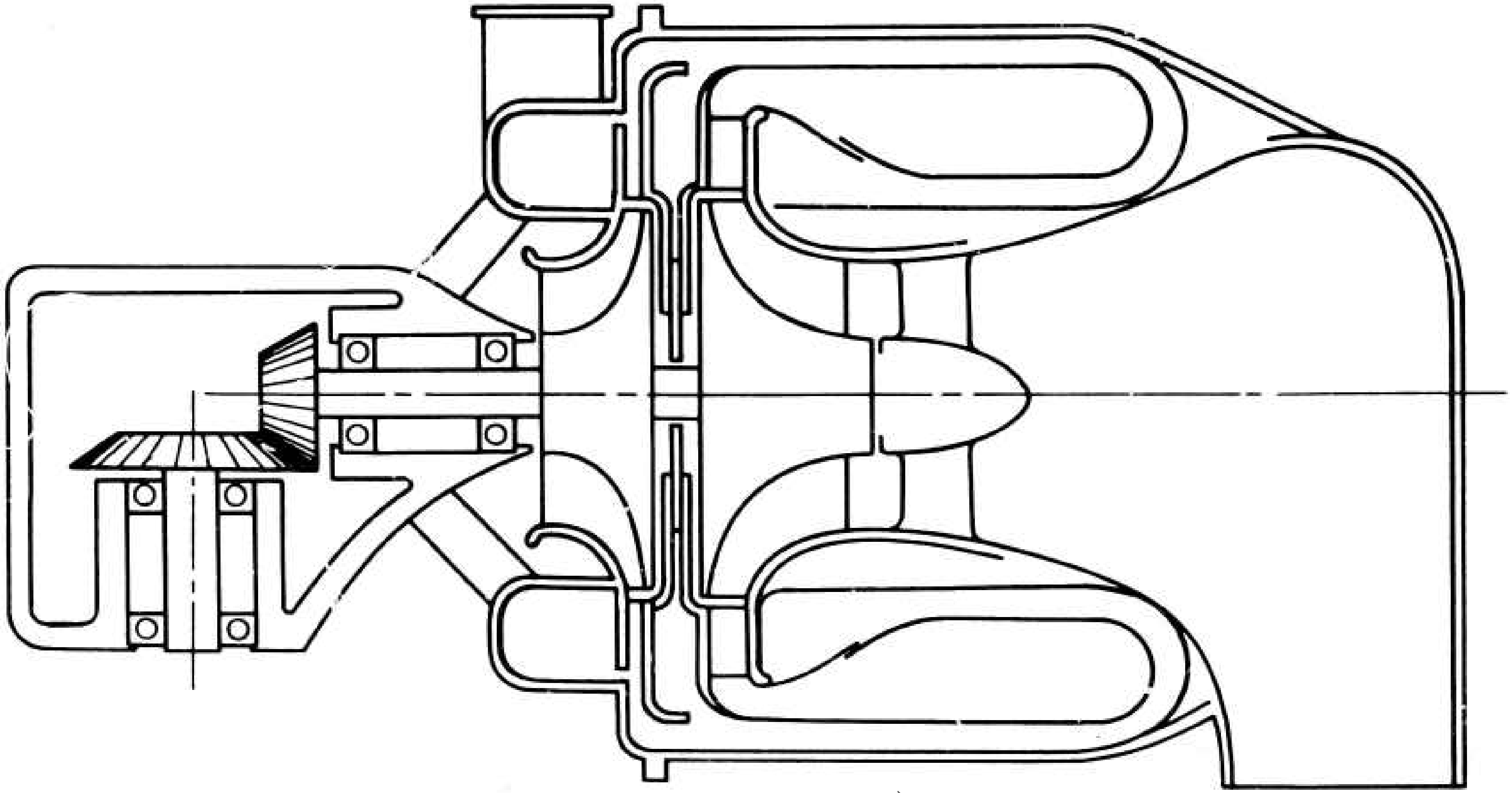


Figure 33. Single-Shaft APU for Bleed Output Only.

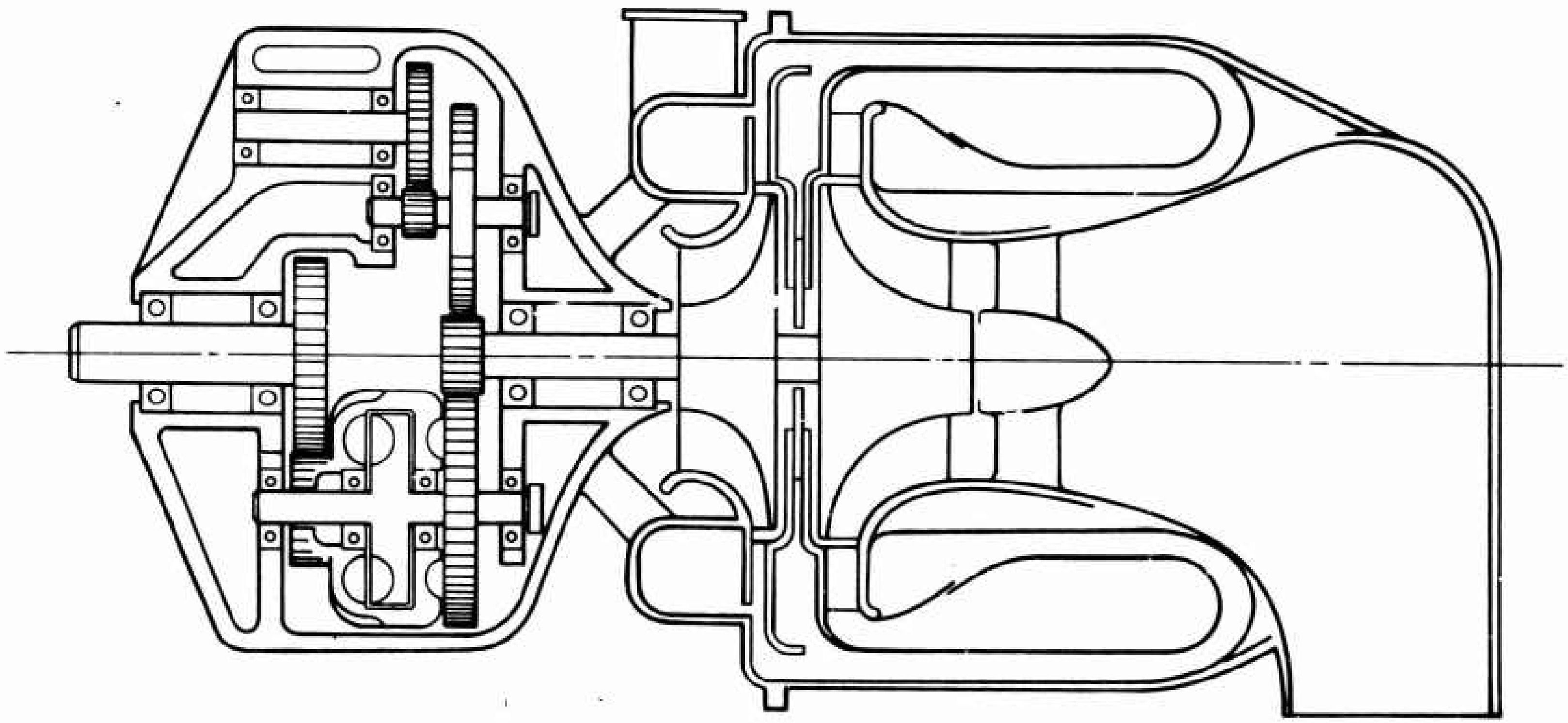


Figure 34. Single-Shaft APU for Bleed and Shaft Power, With Fluid Coupling.

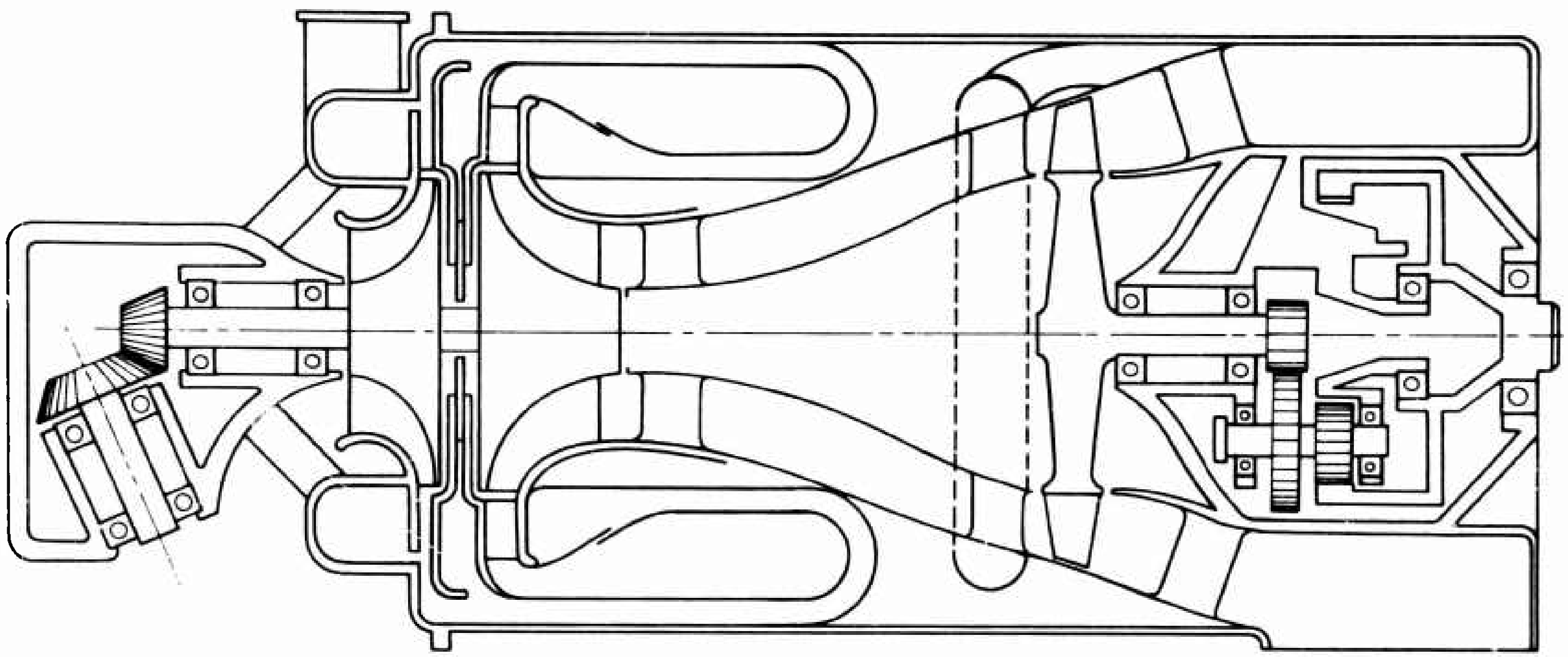


Figure 35. Free-Turbine APU for Bleed and Shaft Power.

TABLE XIII. APU PERFORMANCE AND WEIGHT CHARACTERISTICS

| SPS Config. Designation | A | | | B | | | C | | | D | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| APU Requirements<br>Bleed, Lb/Min.<br>SHP | 20<br>26 | | | 20<br>17 | | | 35<br>- | | | 20<br>17 | | | | |
| Type of APU | Single Shaft Integral Bleed | | | Single Shaft Integral Bleed | | | Single Shaft Integral Bleed | | | Single Shaft Integral Bleed | | | Single Shaft Fluid Coupling Integral Bleed | Free Turbine Integral Bleed |
| Technology Level | 1970 | 1975 | 1985 | 1970 | 1975 | 1985 | 1970 | 1975 | 1985 | 1970 | 1975 | 1985 | 1970 | 1970 |
| Compressor Pressure Ratio | 4:1 | 6:1 | 8:1 | 4:1 | 6:1 | 8:1 | 4:1 | 6:1 | 4:1 | 4:1 | 6:1 | 8:1 | 4:1 | 4:1 |
| Turbine-Inlet Temp. $^{o}F$ | 1800 | 2000 | 2250 | 1800 | 2000 | 2250 | 1800 | 2000 | 2250 | 1800 | 2000 | 2250 | 1800 | 1800 |
| APU Inlet Airflow, Lb/Sec | 1.68 | 1.16 | 0.94 | 1.52 | 1.05 | 0.86 | 2.14 | 1.50 | 1.24 | 1.52 | 1.05 | 0.86 | 1.52 | 1.52 |
| Bleed Fraction of Airflow | .198 | .288 | .354 | .219 | .317 | .387 | .283 | .389 | .470 | .219 | .317 | .387 | .219 | .219 |
| Bleed Pressure Ratio | | 4:1 | | | 4:1 | | | 4:1 | | | 4:1 | | 4:1 | 4:1 |
| Equiv.Shp at $130^{o}F$;<br>at SL Std | 76<br>103 | 74<br>101 | 71<br>99 | 66<br>90 | 64<br>88 | 62<br>87 | 86<br>112 | 82<br>107 | 78<br>101 | 66<br>90 | 64<br>88 | 62<br>87 | 66<br>90 | 66<br>90 |
| APU Weight,lb | 100 | 58 | 36 | 87 | 50 | 32 | 94 | 57 | 37 | 87 | 50 | 32 | 91 | 113 |

| TABLE XIV. WEIGHTING FACTORS FOR EVALUATION OF APU'S | Weighting Factor | Summation |
|---|---|---|
| Weight Group | | |
| Weight | 25 | |
| Volume | 5 | |
| 1/2 Influence on Aircraft Complexity | 4 | |
| Sum of Weight Group | | 34 |
| Cost Group | | |
| Unit Cost | 25 | |
| Maintainability | 5 | |
| 1/2 Influence on Aircraft Complexity | 4 | |
| Sum of Cost Group | | 34 |
| Safety/Reliability Group | | |
| Reliability | 10 | |
| APU Complexity | 9 | |
| Installation Complexity | 8 | |
| Survivability/Vulnerability | 5 | |
| Sum of Safety/Reliability Group | | 32 |
| TOTAL | | 100 |

The results of the APU-configuration trade-off study are presented in Table XV. Where the parameters could be quantified, the weighted ratings of the three options are directly related to the values of the parameters. In other cases, the weighted ratings reflect a judgment of the relative goodness of one option compared with the others. The weight parameters for the APU's are larger than those listed in the table of APU performance and weight characteristics because these weights include APU starters, accumulators, electric motor and pump, and controls. The trade-off study showed the fixed-shaft engine to be definitely superior to both the free-turbine engine and the fixed-shaft APU with a fluid coupling.

Another trade-off study was conducted to determine the relative merits of hydraulic-motor APU starting versus electric-motor starting. The basic criteria established for the APU-starting subsystem were that it be totally self-contained for starting in the ambient temperature range from -25°F to 130°F; that kit additions would be used for starting to -65°F; and that it would have a two-start capability (a modified two-start capability for the hydraulic APU-starting subsystem). The two starting systems are schematically pictured in Figure 36. The modified two-start capability for the hydraulic system means that there would be sufficient energy in the battery to drive the electric motor which powers the hydraulic pump, and to recharge the hydraulic accumulator for a second attempt to start the APU.

The weighting factors assigned for the trade-off study were the same as those assumed for the APU-configuration evaluation. The results are presented in Table XVI. Despite the superior reliability and reduced complexity of electrical starting, the weight and volume of the hydraulic system were far better than the electrical system and led to the selection of hydraulic APU starting. The difference was accentuated for -65°F starting capability, because the electrical system would require additional kit equipment to augment battery power while the hydraulic system would be unchanged.

TABLE XV. APU TRADE-OFF STUDY RESULTS

| Parameter | Weighting Factor | Parameter Value | | | Weighted Rating | | |
|---|---|---|---|---|---|---|---|
| | | Fixed Shaft, Fluid Coupling | Free Turbine | Fixed Shaft | Fixed Shaft, Fluid Coupling | Free Turbine | Fixed Shaft |
| Weight, lb | 25 | 109.2 | 131.2 | 112.5 | 25.0 | 20.0 | 24.4 |
| Unit Cost (2000 Units), $ | 25 | $13,500 | $15,250 | $11,250 | 20.0 | 16.1 | 25.0 |
| Reliability, Failures/1000 hr | 10 | 6.10 | 7.36 | 5.3 | 8.5 | 6.1 | 10.0 |
| SPS Complexity = 1/Rel. | 9 | 1.64 | 1.36 | 1.89 | 6.8 | 4.2 | 9.0 |
| Aircraft Complexity | 8 | Good | Good | Good | 8.0 | 8.0 | 8.0 |
| Integration Complexity | 8 | Good | Good | Good | 8.0 | 8.0 | 8.0 |
| Maintainability | 5 | 6.1 | 7.36 | 5.3 | 4.3 | 3.1 | 5.0 |
| Vulnerability/Survivability | 5 | 1.1 | 1.3 | 1.0 | 4.5 | 3.5 | 5.0 |
| Volume, $in^3$ | 5 | 1.1 | 1.3 | 1.0 | 4.5 | 3.5 | 5.0 |
| Total | 100 | | | | 89.6 | 72.5 | 99.4 |

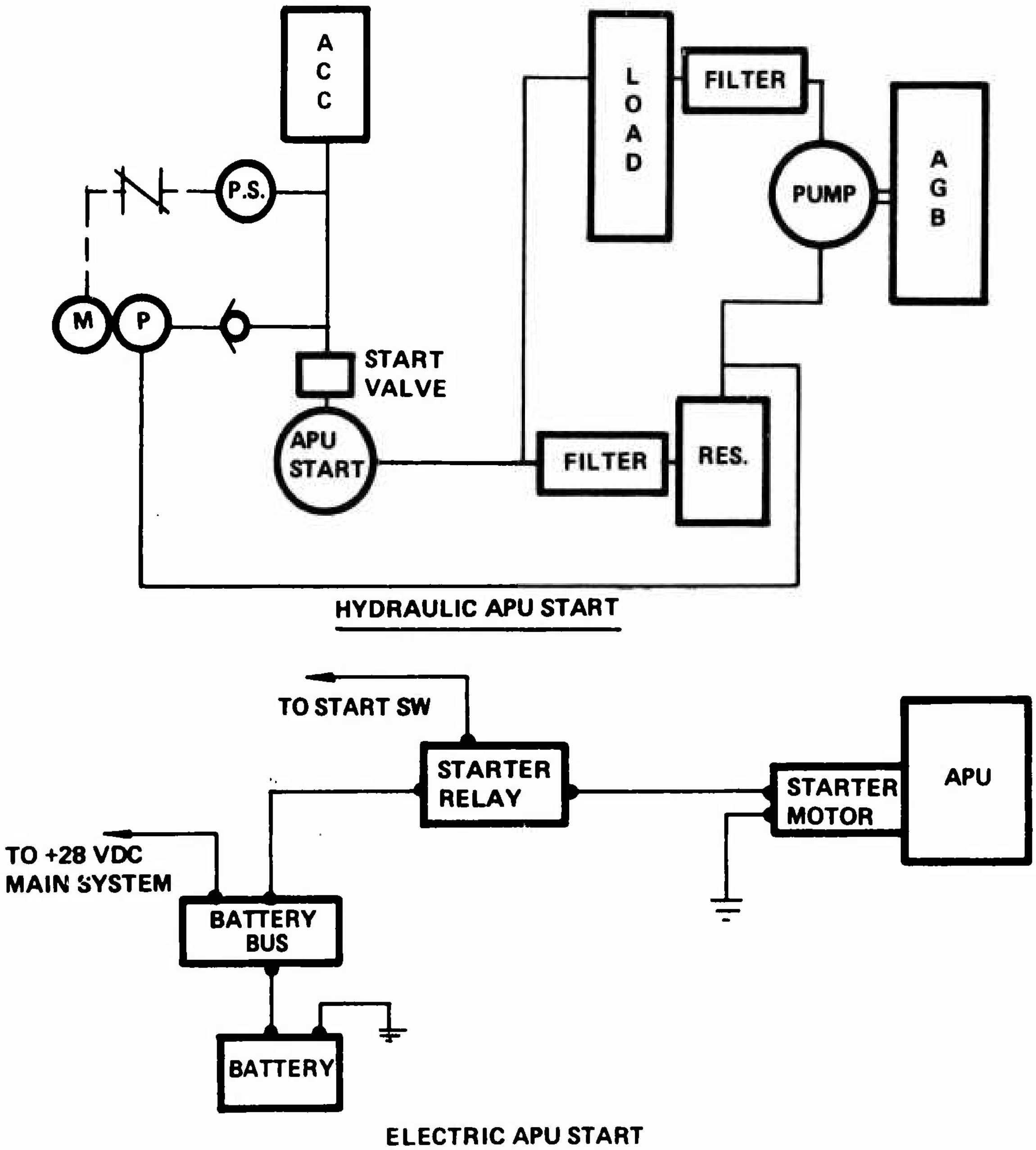



Figure 36. Schematic Diagrams of Electrical and Hydraulic APU Starting Systems.

TABLE XVI. APU-STARTING SYSTEM TRADE-OFF STUDY RESULTS

| Parameter | Weighting Factor | Parameter Value | | Weighted Rating | |
|---|---|---|---|---|---|
| | | Electrical System | Hydraulic System | Electrical System | Hydraulic System |
| -25°F Ambient Temperature Capability | | | | | |
| Weight, lb | 25 | 68.95 | 28 | 10.2 | 25. |
| Unit Cost (2000 Units), $ | 25 | $1379 | $1385 | 25. | 25. |
| Reliability, Failures/1000 hr | 10 | .62 | 2.3 | 10. | 2.7 |
| SPS Complexity = 1/Rel. | 9 | 1.61 | .44 | 9. | 2.4 |
| Aircraft Complexity | 8 | 10 | 8 | 8. | 6.4 |
| Integration Complexity | 8 | 10 | 9 | 8. | 7.2 |
| Maintainability | 5 | Same | Same | 5. | 5. |
| Vulnerability/Survivability | 5 | 1/770 | 1/210 | 1.4 | 5. |
| Volume, $in^3$ | 5 | 770 | 210 | 1.4 | 5. |
| Total | 100 | | | 78.0 | 83.7 |
| -65°F Ambient Temperature Capability | | | | | |
| Weight, lb | 25 | 116.95 | 20 | 6.0 | 25. |
| Unit Cost (2000 Units), $ | 25 | $1969 | $1335 | 17.5 | 25. |
| Reliability, Failures/1000 hr | 10 | .62 | 2.3 | 10. | 2.7 |
| SPS Complexity = 1/Rel. | 9 | 1.61 | .44 | 9. | 2.4 |
| Aircraft Complexity | 8 | 10 | 8 | 8. | 6.4 |
| Integration Complexity | 8 | 10 | 9 | 8. | 7.2 |
| Maintainability | 5 | Same | Same | 5. | 5. |
| Vulnerability/Survivability | 5 | 1/2300 | 1/210 | .5 | 5. |
| Volume, $in^3$ | 5 | 2300 | 210 | .5 | 5. |
| Total | 100 | | | 64.5 | 83.7 |

## COMPARATIVE EVALUATION

Preliminary evaluations and trade-off studies reduced the number of candidate SPS components, and the remaining functional elements were subjected to in-depth analyses for system comparisons. The comparisons were conducted for the baseline system functions and, in addition, for the three possible options which have previously been defined: baseline plus cockpit environmental control system and/or main-engine starting with an inoperable APU. Candidate systems were evaluated on the basis of the following parameters:

- SPS weight
- Impact on aircraft TOGW
- SPS life-cycle cost
- Reliability
- Dispatch availability
- Aircraft complexity
- SPS complexity
- SPS integration complexity
- Maintainability
- Influence on aircraft range
- Power requirements
- Volume
- Vulnerability

The comparative evaluation provided technical substantiation for system selection, identifying advantages and disadvantages of candidate systems, with particular emphasis on aspects related to impact on aircraft design and systems integration.

## CANDIDATE SPS DATA

Tabulations of weight data for SPS configurations A, B, C, and D are listed in Tables XVII through XX. Each table provides weight parameters for the three levels of technology considered in the study: existing technology (1970) and technology applicable to 1975- and 1985-production aircraft. Tables XXI and XXII also provide incremental component weight data for the three system functional options, in addition to the data for the baseline system, and the weight summary.

SPS component volumes are listed in Table XXIII, and Table XXIV summarizes the system volumes for the four functional options considered.

| TABLE XVII. SPS WEIGHTS, CONFIGURATION A | | | |
|---|---|---|---|
| | Weight (lb) | | |
| | 1970 | 1975 | 1985 |
| ENGINE STARTING SYSTEM | (37.4) | (33.0) | (29.7) |
| Hydraulic Motors | 9.0 | 7.0 | 6.0 |
| Controls (valves, etc.) | 10.0 | 9.0 | 8.0 |
| Plumbing, Oil and Wiring | 15.0 | 14.0 | 13.0 |
| Installation | 3.4 | 3.0 | 2.7 |
| AUXILIARY POWER PLANT | (150.2) | (95.9) | (67.1) |
| APU | 100.0 | 58.0 | 36.0 |
| APU Starting | | | |
| Hydraulic Motor | 4.0 | 3.5 | 3.0 |
| Accumulator | 6.6 | 6.3 | 6.0 |
| Plumbing, Oil and Wiring | 2.9 | 2.9 | 2.9 |
| Electric Motor/Pump | 3.6 | 3.0 | 2.9 |
| Controls | 3.1 | 3.0 | 2.9 |
| Installation | 30.0 | 19.2 | 13.4 |
| ACCESSORY GEARBOX | (76.2) | (67.3) | (62.7) |
| Gearbox | 45.0 | 40.0 | 38.0 |
| Gearbox Installation | 9.0 | 8.0 | 7.6 |
| Gearbox Drive | | | |
| Hydraulic Motor | 5.5 | 4.2 | 3.8 |
| Controls, Plumbing, Oil, Wiring | 13.0 | 11.9 | 10.8 |
| Installation | 3.7 | 3.2 | 2.5 |
| ECS | (125.0) | (120.0) | (114.0) |
| Cabin Vent System (fans, ducting, controls, wiring) | 84.0 | 81.0 | 77.0 |
| Heating System (heat exchanger, bleed system, controls, wiring) | 20.0 | 18.0 | 16.0 |
| Avionics Bay Cooling (fan, ducts, wiring) | 10.0 | 10.0 | 10.0 |
| Installation | 11.0 | 11.0 | 11.0 |
| HYDRAULIC PUMP SYSTEM | (23.1) | (19.8) | (15.4) |
| Pump Packages (including filters, reservoirs, valves, wiring, etc.) | 21.0 | 18.0 | 14.0 |
| Installation | 2.1 | 1.8 | 1.4 |
| ELECTRIC POWER GENERATION | (72.2) | (61.6) | (46.8) |
| Generators | 50.0 | 42.0 | 32.0 |
| Control Units and Wiring | 15.6 | 14.0 | 10.5 |
| Installation | 6.6 | 5.6 | 4.3 |
| TOTAL | 484.1 | 397.6 | 335.7 |

TABLE XVIII. SPS WEIGHTS, CONFIGURATION B

| | Weight (lb) | | |
|---|---|---|---|
| | 1970 | 1975 | 1985 |
| ENGINE STARTING SYSTEM | (37.4) | (33.0) | (29.7) |
| Hydraulic Motors | 9.0 | 7.0 | 6.0 |
| Controls (valves, etc.) | 10.0 | 9.0 | 8.0 |
| Plumbing, Oil and Wiring | 15.0 | 14.0 | 13.0 |
| Installation | 3.4 | 3.0 | 2.7 |
| AUXILIARY POWER PLANT | (145.9) | (96.5) | (71.6) |
| APU | 87.0 | 50.0 | 32.0 |
| APU Starting | | | |
| Hydraulic Motor | 7.0 | 6.0 | 5.0 |
| Accumulator | 10.1 | 9.5 | 9.0 |
| Plumbing, Oil, Wiring | 5.9 | 5.7 | 5.5 |
| Electric Motor/Pump | 3.6 | 3.0 | 2.9 |
| Controls | 3.1 | 3.0 | 2.9 |
| Installation | 29.2 | 19.3 | 14.3 |
| ACCESSORY GEARBOX | (77.4) | (69.1) | (65.5) |
| Gearbox | 56.0 | 50.5 | 48.0 |
| Installation | 11.2 | 10.1 | 9.6 |
| Utility Hydraulic Pump/Plumbing | 10.2 | 8.5 | 7.9 |
| ECS | (125.0) | (120.0) | (114.0) |
| Cabin Vent System (fans, ducting, controls, wiring) | 84.0 | 81.0 | 77.0 |
| Heating System (heat exchanger, bleed system, controls, wiring) | 28.0 | 18.0 | 16.0 |
| Avionics Bay Cooling (fan, ducts, wiring) | 10.0 | 10.0 | 10.0 |
| Installation | 11.0 | 11.0 | 11.0 |
| HYDRAULIC PUMP SYSTEM | (23.1) | (19.8) | (15.4) |
| Pump Packages (including filters, reservoirs, valves, wiring, etc.) | 21.0 | 18.0 | 14.0 |
| Installation | 2.1 | 1.8 | 1.4 |
| ELECTRIC POWER GENERATION | (72.2) | (61.6) | (46.8) |
| Generators | 50.0 | 42.0 | 32.0 |
| Control Units and Wiring | 15.6 | 14.0 | 10.5 |
| Installation | 6.6 | 5.6 | 4.3 |
| TOTAL | 481.0 | 400.0 | 343.0 |

TABLE XIX. SPS WEIGHTS, CONFIGURATION C

| | Weight (lb) | | |
|---|---|---|---|
| | 1970 | 1975 | 1985 |
| ENGINE STARTING SYSTEM | (39.6) | (33.9) | (29.3) |
| ATS | 21.0 | 18.0 | 15.0 |
| Controls (valves, etc.) | 10.0 | 8.0 | 7.0 |
| Plumbing and Wiring | 5.0 | 4.8 | 4.6 |
| Installation | 3.6 | 3.1 | 2.7 |
| AUXILIARY POWER PLANT | (142.8) | (94.6) | (68.4) |
| APU | 94.0 | 57.0 | 37.0 |
| APU Starting | | | |
| Hydraulic Motor | 4.0 | 3.5 | 3.0 |
| Accumulator | 6.6 | 6.3 | 6.0 |
| Plumbing, Oil and Wiring | 2.9 | 2.9 | 2.9 |
| Electric Motor/Pump | 3.6 | 3.0 | 2.9 |
| Controls | 3.1 | 3.0 | 2.9 |
| Installation | 28.6 | 18.9 | 13.7 |
| ACCESSORY GEARBOX | (78.0) | (68.6) | (64.8) |
| Gearbox | 45.0 | 40.0 | 38.0 |
| Gearbox Installation | 9.0 | 8.0 | 7.6 |
| Gearbox Drive | | | |
| ATM | 10.0 | 8.6 | 8.0 |
| Controls | 10.0 | 8.6 | 8.0 |
| Installation | 4.0 | 3.4 | 3.2 |
| ECS | (125.0) | (120.0) | (114.0) |
| Cabin Vent System (fans, ducting, controls,wiring) | 84.0 | 81.0 | 77.0 |
| Heating System (heat exchanger, bleed system, controls, wiring) | 20.0 | 18.0 | 16.0 |
| Avionics Bay Cooling (fan, ducts, wiring) | 10.0 | 10.0 | 10.0 |
| Installation | 11.0 | 11.0 | 11.0 |
| HYDRAULIC PUMP SYSTEM | (23.1) | (19.8) | (15.4) |
| Pump Packages (including filters, reservoirs,valves,wiring,etc.) | 21.0 | 18.0 | 14.0 |
| Installation | 2.1 | 1.8 | 1.4 |
| ELECTRIC POWER GENERATION | (72.2) | (61.6) | (46.8) |
| Generators | 50.0 | 42.0 | 32.0 |
| Control Units and Wiring | 15.6 | 14.0 | 10.5 |
| Installation | 6.6 | 5.6 | 4.3 |
| TOTAL | 480.7 | 398.5 | 338.7 |

| TABLE XX. SPS WEIGHTS, CONFIGURATION D | | | |
|---|---|---|---|
| | Weight (lb) | | |
| | 1970 | 1975 | 1985 |
| ENGINE STARTING SYSTEM | (39.6) | (33.9) | (29.3) |
| ATS | 21.0 | 18.0 | 15.0 |
| Controls (valves, etc.) | 10.0 | 8.0 | 7.0 |
| Plumbing and Wiring | 5.0 | 4.8 | 4.6 |
| Installation | 3.6 | 3.1 | 2.7 |
| AUXILIARY POWER PLANT | (145.5) | (98.2) | (73.4) |
| APU | 87.0 | 50.0 | 32.0 |
| APU Starting | | | |
| Hydraulic Motor | 7.0 | 6.0 | 5.0 |
| Accumulator | 10.1 | 9.5 | 9.0 |
| Plumbing, Oil and Wiring | 5.9 | 5.7 | 5.5 |
| Electric Motor/Pump | 3.6 | 3.0 | 2.9 |
| Controls | 3.1 | 3.0 | 2.9 |
| Installation | 28.8 | 21.0 | 16.1 |
| ACCESSORY GEARBOX | (60.0) | (54.0) | (51.6) |
| Gearbox | 50.0 | 45.0 | 43.0 |
| Installation | 10.0 | 9.0 | 8.6 |
| ECS | (125.0) | (120.0) | (114.0) |
| Cabin Vent System (fans, ducting, controls, wiring) | 84.0 | 81.0 | 77.0 |
| Heating System (heat exchanger, bleed system, controls, wiring) | 20.0 | 18.0 | 16.0 |
| Avionics Bay Cooling (fan, ducts, wiring) | 10.0 | 10.0 | 10.0 |
| Installation | 11.0 | 11.0 | 11.0 |
| HYDRAULIC PUMP SYSTEM | (23.1) | (19.8) | (15.4) |
| Pump Packages (including filters, reservoirs, valves, wiring, etc.) | 21.0 | 18.0 | 14.0 |
| Installation | 2.1 | 1.8 | 1.4 |
| ELECTRIC POWER GENERATION | (72.2) | (61.6) | (46.8) |
| Generators | 50.0 | 42.0 | 32.0 |
| Control Units and Wiring | 15.6 | 14.0 | 10.5 |
| Installation | 6.6 | 5.6 | 4.3 |
| TOTAL | 465.4 | 387.5 | 330.5 |

TABLE XXI. WEIGHTS OF SPS OPTIONS

| Option | | Added Weight (lb) | |
|---|---|---|---|
| | 1970 | 1975 | 1985 |
| COCKPIT COOLING (All SPS Configurations) | | | |
| Air Cycle Pack | 26.0 | 24.5 | 23.5 |
| Controls and Wiring | 3.0 | 3.0 | 3.0 |
| Installation | 2.6 | 2.5 | 2.4 |
| TOTAL | 31.6 | 30.0 | 28.9 |
| BACKUP ENGINE START | | | |
| Configuration A or B | 47.3 | 39.6 | 35.2 |
| Configuration C or D | 24.3 | 24.2 | 20.9 |

TABLE XXII. SPS WEIGHT SUMMARY

| Conf. | Cockpit Cooling | | Backup Start | | Weight (lb) | | |
|---|---|---|---|---|---|---|---|
| | With | Without | With | Without | 1970 | 1975 | 1985 |
| A | | X | | X | 484.1 | 397.6 | 335.7 |
| B | | X | | X | 481.0 | 400.0 | 343.0 |
| C | | X | | X | 480.7 | 398.5 | 338.7 |
| D | | X | | X | 465.4 | 387.5 | 330.5 |
| A | X | | | X | 515.7 | 427.6 | 364.6 |
| B | X | | | X | 512.6 | 430.0 | 371.9 |
| C | X | | | X | 512.3 | 428.5 | 367.6 |
| D | X | | | X | 497.0 | 417.5 | 359.4 |
| A | | X | X | | 531.4 | 437.2 | 370.9 |
| B | | X | X | | 528.3 | 439.6 | 378.2 |
| C | | X | X | | 505.0 | 422.7 | 359.6 |
| D | | X | X | | 489.7 | 411.7 | 351.4 |
| A | X | | X | | 563.0 | 467.2 | 399.8 |
| B | X | | X | | 559.9 | 469.6 | 407.1 |
| C | X | | X | | 536.6 | 456.7 | 388.5 |
| D | X | | X | | 521.3 | 441.7 | 380.3 |

TABLE XXIII. SPS COMPONENT VOLUMES

| | Volume - cubic feet | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SPS Configuration | A | | | B | | | C | | | D | | |
| Level of Technology | 1970 | 1975 | 1985 | 1970 | 1975 | 1985 | 1970 | 1975 | 1985 | 1970 | 1975 | 1985 |
| Baseline Components | | | | | | | | | | | | |
| APU | .50 | .54 | .51 | .48 | .46 | .45 | .44 | .42 | .40 | .48 | .46 | .44 |
| AGB | .85 | .75 | .71 | .94 | .85 | .81 | .85 | .75 | .71 | .85 | .75 | .71 |
| Engine Start System | | | | | | | | | | | | |
| Hyd Start Motors (2) | .05 | .04 | .04 | .05 | .04 | .04 | | | | | | |
| AGB Pump/Pump Motor | .02 | .02 | .02 | .02 | .02 | .02 | | | | | | |
| Hyd Controls | .03 | .03 | .03 | .02 | .02 | .02 | | | | | | |
| Piping | .04 | .04 | .04 | .02 | .02 | .02 | | | | | | |
| ATS (2) | | | | | | | .09 | .08 | .07 | .09 | .08 | .07 |
| Ducting | | | | | | | .07 | .07 | .07 | .07 | .07 | .07 |
| APU Start System | | | | | | | 1.22 | 1.22 | 1.22 | .58 | .58 | .58 |
| Electric Generators(2) | .41 | .40 | .29 | .41 | .40 | .29 | .41 | .40 | .29 | .41 | .40 | .29 |
| Electric Control Units | .19 | .19 | .11 | .19 | .19 | .11 | .19 | .19 | .11 | .19 | .19 | .11 |
| Flight Pumps (2) | | | | | | | | | | | | |
| SUBTOTALS | 2.12 | 2.04 | 1.78 | 2.16 | 2.03 | 1.79 | 3.30 | 3.16 | 2.90 | 2.70 | 2.56 | 2.30 |
| Cockpit ECS | | | | | | | | | | | | |
| Cockpit ECS | .72 | .70 | .63 | .72 | .70 | .63 | .72 | .70 | .63 | .72 | .70 | .63 |
| ECS Ducts | .36 | .36 | .36 | .36 | .36 | .36 | .36 | .36 | .36 | .36 | .36 | .36 |
| ECS TOTALS | 1.08 | 1.06 | .99 | 1.08 | 1.06 | .99 | 1.08 | 1.06 | .99 | 1.08 | 1.06 | .99 |
| Backup Starting | | | | | | | | | | | | |
| Cartridge-Hyd.Pump* | .08 | .07 | .06 | .08 | .07 | .06 | | | | | | |
| Cartridge-Pneu.Starter | | | | | | | .09 | .09 | .07 | .09 | .09 | .07 |
| Eng. Gearbox | | | | | | | .02 | .02 | .02 | .02 | .02 | .02 |
| BACKUP STARTING TOTALS | .08 | .07 | .06 | .08 | .07 | .06 | .11 | .11 | .09 | .11 | .11 | .09 |

*Incremental Increase to one Hydraulic Starting Motor

TABLE XXIV. SPS VOLUME SUMMARY

| | Volume-cubic feet | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SPS Configuration | A | | | B | | | C | | | D | | |
| Level of Technology | 1970 | 1975 | 1985 | 1970 | 1975 | 1985 | 1970 | 1975 | 1985 | 1970 | 1975 | 1985 |
| 1) BASIC SYSTEM WITHOUT COCKPIT COOLING WITHOUT BACKUP STARTING | 2.28 | 2.16 | 1.89 | 2.28 | 2.18 | 1.90 | 3.40 | 3.26 | 3.00 | 2.82 | 2.69 | 2.42 |
| 2) BASIC SYSTEM WITH COCKPIT COOLING WITHOUT BACKUP STARTING | 3.36 | 3.21 | 2.88 | 3.37 | 3.24 | 2.90 | 4.48 | 4.32 | 3.99 | 3.90 | 3.74 | 3.42 |
| 3) BASIC SYSTEM WITHOUT COCKPIT COOLING WITH BACKUP STARTING | 2.38 | 2.23 | 1.95 | 2.37 | 2.25 | 1.97 | 3.51 | 3.37 | 3.10 | 2.93 | 2.80 | 2.52 |
| 4) BASIC SYSTEM WITH COCKPIT COOLING WITH BACKUP STARTING | 3.45 | 3.28 | 2.95 | 3.45 | 3.31 | 2.96 | 4.59 | 4.43 | 4.09 | 4.02 | 3.86 | 3.52 |

Predicted failure rates for the SPS are contained in Tables XXV through XXIX. The following definitions apply to the parameters in the tables:

1. Base TMR is the base total malfunction rate - the predicted failure rate for existing technology components per thousand hours.

2. Adjustment factor is the multiplication factor applied to the failure rate to represent the anticipated reduction as technology advances.

3. The ratio of malfunction-induced removals to total malfunction rate is MIR/TMR.

4. Duty cycle is the ratio of total operating time (ground and flight) to flight operating time.

5. Total malfunction rate (TMR) and malfunction-induced removals (MIR) are expressed per thousand hours.

Reference 3 provided some of the failure rate data, and other data were supplied by SPS component manufacturers in response to the industry surveys conducted early in this program.

Table XXX summarizes the results of an analysis of the probability that an engine start could not be accomplished due to failures in the SPS. Mission-affecting failure rates used in the analysis were obtained from the references listed above. Block diagram analyses of APU/APU-starting, and hydraulic and pneumatic main-engine starting, are pictured in Figures 37, 38, and 39.

An analysis of maintenance requirements was made to determine:

1. What is required - repair on aircraft, replace, repair off aircraft, test, adjust.

2. Where maintenance is required - organization, direct support (D.S.), general support (G.S.), or depot levels.

3. Time and man-loading to accomplish maintenance.

TABLE XXV. SPS COMPONENT FAILURE RATES - CONFIGURATION A

| CONFIGURATION A<br>WITH COCKPIT COOLING, AND WITH BACKUP START | BASE TMR | ADJUSTMENT FACTOR 1970 | ADJUSTMENT FACTOR 1875 | ADJUSTMENT FACTOR 1985 | RATIO MIR TO TMR | QTY PER ACFT | DUTY CYCLE | SYSTEM TMR 1970 | SYSTEM TMR 1975 | SYSTEM TMR 1985 | SYSTEM MIR 1970 | SYSTEM MIR 1975 | SYSTEM MIR 1985 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ENGINE START SYSTEM | | | | | | | | | | | | | |
| HYDRAULIC | | | | | | | | | | | | | |
| MOTOR | .600 | 1.0 | .67 | .45 | .67 | 2 | 1 | 1.20 | .80 | .54 | .80 | .54 | .36 |
| VALVE | .250 | 1.0 | .67 | .45 | .60 | 5 | 1 | 1.25 | .84 | .56 | .75 | .50 | .34 |
| PLUMBING | .650 | 1.0 | .67 | .45 | .38 | 1 | 1 | .65 | .44 | .29 | .25 | .17 | .11 |
| PNEUMATIC | | | | | | | | | | | | | |
| MOTOR | .396 | 1.0 | .82 | .70 | .23 | | | | | | | | |
| VALVE | .225 | 1.0 | .82 | .70 | .60 | | | | | | | | |
| PLUMBING | .027 | 1.0 | .82 | .70 | .40 | | | | | | | | |
| BACKUP START | | | | | | | | | | | | | |
| HYDRAULIC (CONTROL, PACK, PLUMBING) | 2.47 | 1.0 | .82 | .70 | .50 | 1 | .007 | .01 | .01 | .01 | .01 | .01 | .01 |
| PNEUMATIC | | | | | | | | | | | | | |
| CARTRIDGE STARTER | .44 | 1.0 | .82 | .70 | .23 | | | | | | | | |
| CARTRIDGE & CONTROL | .34 | 1.0 | .82 | .70 | .50 | | | | | | | | |
| AUXILIARY POWER PLANT | | | | | | | | | | | | | |
| APU | 5.300 | 1.0 | .82 | .70 | .21 | 1 | 1 | 5.30 | 4.35 | 3.71 | 1.11 | .91 | .78 |
| HYDRAULIC START | | | | | | | | | | | | | |
| MOTOR | .600 | 1.0 | .67 | .45 | .67 | | | | | | | | |
| MOTOR/PUMP | .950 | 1.0 | .67 | .45 | .67 | 1 | 1 | .95 | .64 | .43 | .64 | .43 | .29 |
| ACCUMULATOR | .500 | 1.0 | .90 | .85 | .40 | 1 | 1 | .50 | .45 | .43 | .20 | .18 | .17 |
| ELECTRIC MOTOR PUMP | .520 | 1.0 | .82 | .70 | .67 | 1 | 1 | .52 | .43 | .36 | .35 | .29 | .24 |
| VALVE | .250 | 1.0 | .70 | .50 | .67 | 1 | 1 | .25 | .18 | .13 | .16 | .12 | .08 |
| ACCESSORY GEARBOX | | | | | | | | | | | | | |
| GEARBOX | .188 | 1.0 | .90 | .85 | .23 | 1 | 1.33 | .25 | .23 | .21 | .06 | .05 | .05 |
| OVERRUNNING CLUTCH | .074 | 1.0 | .90 | .85 | 1.0 | 1 | 1.00 | .07 | .07 | .06 | .07 | .07 | .06 |
| DRIVE | | | | | | | | | | | | | |
| HYDRAULIC MOTOR | .570 | 1.0 | .82 | .70 | .67 | | | | | | | | |
| HYD MOTOR/PUMP | .950 | 1.0 | .67 | .45 | .67 | 1 | 1.33 | 1.26 | .85 | .57 | .85 | .57 | .38 |
| ATM | .417 | 1.0 | .90 | .85 | .23 | | | | | | | | |
| AIR CONDITIONING | | | | | | | | | | | | | |
| CABIN HEAT VENT SYSTEM | 1.000 | 1.0 | .82 | .70 | .50 | 1 | 1.33 | 1.33 | 1.09 | .93 | .67 | .55 | .47 |
| AVIONICS COOLING SYSTEM | .750 | 1.0 | .82 | .70 | .50 | 1 | 1.33 | 1.00 | .82 | .70 | .50 | .41 | .35 |
| COCKPIT COOLING | 1.050 | 1.0 | .82 | .70 | .50 | 1 | 1.33 | 1.40 | 1.04 | .96 | .70 | .52 | .49 |
| HYDRAULIC PUMP SYSTEM | | | | | | | | | | | | | |
| PUMP PACKS | .950 | 1.0 | .67 | .45 | .67 | 2 | 1.33 | 2.53 | 1.69 | 1.14 | 1.69 | 1.13 | .76 |
| PLUMBING & FILTERS | 1.280 | 1.0 | .67 | .45 | .38 | 1 | 1.33 | 1.70 | 1.14 | .77 | .65 | .43 | .29 |
| CHECK & RELIEF VALVES | .440 | 1.0 | .67 | .45 | .60 | 14 | 1.33 | 8.19 | 5.49 | 3.68 | 4.92 | 3.29 | 2.21 |
| ELECTRIC POWER GENERATION | | | | | | | | | | | | | |
| GENERATORS | .128 | 1.0 | .82 | .70 | 1.0 | 2 | 1.33 | .34 | .28 | .24 | .34 | .28 | .24 |
| CONTROL UNITS | .131 | 1.0 | .56 | .44 | 1.0 | 2 | 1.33 | .35 | .20 | .15 | .35 | .20 | .15 |
| TRANSFORMER-RECTIFIERS | .130 | 1.0 | .82 | .70 | 1.0 | 2 | 1.33 | .35 | .28 | .24 | .35 | .28 | .24 |
| SUM OF FAILURE RATES | | | | | | | | 29.4 | 21.3 | 16.1 | | | |

TABLE XXVI. SPS COMPONENT FAILURE RATES - CONFIGURATION B

| CONFIGURATION B<br>WITH COCKPIT COOLING, AND WITH BACKUP START | BASE TMR | ADJUSTMENT FACTOR | | | RATIO MIR TO TMR | QTY PER ACFT | DUTY CYCLE | SYSTEM TMR | | | SYSTEM MIR | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1970 | 1975 | 1985 | | | | 1970 | 1975 | 1985 | 1970 | 1975 | 1985 |
| ENGINE START SYSTEM | | | | | | | | | | | | | |
| HYDRAULIC | | | | | | | | | | | | | |
| MOTOR | .600 | 1.0 | .67 | .45 | .67 | 2 | 1 | 1.20 | .80 | .54 | .80 | .54 | .36 |
| VALVE | .250 | 1.0 | .67 | .45 | .60 | 1 | 1 | 1.25 | .84 | .56 | .75 | .50 | .34 |
| PLUMBING | .650 | 1.0 | .67 | .45 | .38 | 1 | 1 | .65 | .44 | .29 | .25 | .17 | .11 |
| PNEUMATIC | | | | | | | | | | | | | |
| MOTOR | .396 | 1.0 | .82 | .70 | .23 | | | | | | | | |
| VALVE | .225 | 1.0 | .82 | .70 | .60 | | | | | | | | |
| PLUMBING | .027 | 1.0 | .82 | .70 | .40 | | | | | | | | |
| BACKUP START | | | | | | | | | | | | | |
| HYDRAULIC (CONTROL, PACK, PLUMBING) | 2.47 | 1.0 | .82 | .70 | .50 | 1 | .007 | .01 | .01 | .01 | .01 | .01 | .01 |
| PNEUMATIC | | | | | | | | | | | | | |
| CARTRIDGE STARTER | .44 | 1.0 | .82 | .70 | .23 | | | | | | | | |
| CARTRIDGE & CONTROL | .34 | 1.0 | .82 | .70 | .50 | | | | | | | | |
| AUXILIARY POWER PLANT | | | | | | | | | | | | | |
| APU | 5.300 | 1.0 | .82 | .70 | .21 | 1 | 1 | 5.30 | 4.35 | 3.71 | 1.11 | .91 | .78 |
| HYDRAULIC START | | | | | | | | | | | | | |
| MOTOR | .600 | 1.0 | .67 | .45 | .67 | 1 | 1 | .60 | .40 | .27 | .40 | .27 | .18 |
| MOTOR/PUMP | .950 | 1.0 | .67 | .45 | .67 | | | | | | | | |
| ACCUMULATOR | .500 | 1.0 | .90 | .85 | .40 | 1 | 1 | .50 | .45 | .43 | .20 | .18 | .17 |
| ELECTRIC MOTOR PUMP | .520 | 1.0 | .82 | .70 | .67 | 1 | 1 | .52 | .43 | .36 | .35 | .29 | .24 |
| VALVE | .250 | 1.0 | .70 | .50 | .67 | 1 | 1 | .25 | .18 | .13 | .17 | .12 | .08 |
| ACCESSORY GEARBOX | | | | | | | | | | | | | |
| GEAR BOX | .188 | 1.0 | .90 | .85 | .23 | 1 | 1.33 | .25 | .23 | .21 | .06 | .05 | .05 |
| OVERRUNNING CLUTCH | .074 | 1.0 | .90 | .85 | 1.0 | 2 | .67 | .10 | .09 | .08 | .10 | .09 | .08 |
| DRIVE | | | | | | | | | | | | | |
| HYDRAULIC MOTOR | .570 | 1.0 | .82 | .70 | .67 | | | | | | | | |
| HYD MOTOR/PUMP | .950 | 1.0 | .67 | .45 | .67 | | | | | | | | |
| ATM | .417 | 1.0 | .90 | .85 | .23 | | | | | | | | |
| AIR CONDITIONING | | | | | | | | | | | | | |
| CABIN HEAT VENT SYSTEM | 1.000 | 1.0 | .82 | .70 | .50 | 1 | 1.33 | 1.33 | 1.09 | .93 | .67 | .55 | .47 |
| AVIONICS COOLING SYSTEM | .750 | 1.0 | .82 | .70 | .50 | 1 | 1.33 | 1.00 | .82 | .70 | .50 | .41 | .35 |
| COCKPIT COOLING | 1.050 | 1.0 | .82 | .70 | .50 | 1 | 1.33 | 1.40 | 1.04 | .98 | .70 | .52 | .49 |
| HYDRAULIC PUMP SYSTEM | | | | | | | | | | | | | |
| PUMP PACKS | .950 | 1.0 | .67 | .45 | .67 | 3 | 1.33 | 3.79 | 2.54 | 1.71 | 2.54 | 1.70 | 1.14 |
| PLUMBING & FILTERS | 1.280 | 1.0 | .67 | .45 | .38 | 1 | 1.33 | 1.70 | 1.41 | .77 | .65 | .43 | .29 |
| CHECK & RELIEF VALVES | .440 | 1.0 | .67 | .45 | .60 | 11 | 1.33 | 6.44 | 4.31 | 2.90 | 3.86 | 2.59 | 1.74 |
| ELECTRIC POWER GENERATION | | | | | | | | | | | | | |
| GENERATORS | .128 | 1.0 | .82 | .70 | 1.0 | 2 | 1.33 | .34 | .28 | .24 | .34 | .28 | .24 |
| CONTROL UNITS | .131 | 1.0 | .56 | .44 | 1.0 | 2 | 1.33 | .35 | .28 | .24 | .35 | .28 | .24 |
| TRANSFORMER-RECTIFIERS | .130 | 1.0 | .82 | .70 | 1.0 | 2 | 1.33 | .35 | .20 | .15 | .35 | .20 | .15 |
| SUM OF FAILURE RATES | | | | | | | | 27.3 | 20.2 | 15.2 | | | |

| TABLE XXVII. SPS COMPONENT FAILURE RATES - CONFIGURATION C | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CONFIGURATION C | BASE TMR | ADJUSTMENT FACTOR | | | RATIO MIR TO TMR | QTY PER ACFT | DUTY CYCLE | SYSTEM TMR | | | SYSTEM MIR | | |
| WITH COCKPIT COOLING, AND WITH BACKUP START | | 1970 | 1975 | 1985 | | | | 1970 | 1975 | 1985 | 1970 | 1975 | 1985 |
| **ENGINE START SYSTEM** | | | | | | | | | | | | | |
| **HYDRAULIC** | | | | | | | | | | | | | |
| MOTOR | .600 | 1.0 | .67 | .45 | .67 | | | | | | | | |
| VALVE | .250 | 1.0 | .67 | .45 | .60 | | | | | | | | |
| PLUMBING | .850 | 1.0 | .67 | .45 | .38 | | | | | | | | |
| **PNEUMATIC** | | | | | | | | | | | | | |
| MOTOR | .396 | 1.0 | .82 | .70 | .23 | 1 | 1.0 | .40 | .33 | .28 | .09 | .08 | .06 |
| VALVE | .225 | 1.0 | .82 | .70 | .60 | 3 | 1.0 | .68 | .55 | .47 | .41 | .33 | .28 |
| PLUMBING | .027 | 1.0 | .82 | .70 | .40 | 1 | 1.1 | .03 | .02 | .02 | .01 | .01 | .01 |
| **BACKUP START** | | | | | | | | | | | | | |
| HYDRAULIC (CONTROL, PACK, PLUMBING) | 2.47 | 1.0 | .82 | .70 | .50 | | | | | | | | |
| **PNEUMATIC** | | | | | | | | | | | | | |
| CARTRIDGE STARTER | .44 | 1.0 | .82 | .70 | .23 | 1 | 1 | .44 | .36 | .31 | .10 | .08 | .07 |
| CARTRIDGE & CONTROL | .34 | 1.0 | .82 | .70 | .50 | 1 | .004 | .00 | .00 | .00 | .00 | .00 | .00 |
| **AUXILIARY POWER PLANT** | | | | | | | | | | | | | |
| **APU** | 5.300 | 1.0 | .82 | .70 | .21 | 1 | 1 | 5.30 | 4.35 | 3.71 | 1.11 | .91 | .78 |
| **HYDRAULIC START** | | | | | | | | | | | | | |
| MOTOR | .600 | 1.0 | .67 | .45 | .67 | 1 | 1 | .60 | .40 | .27 | .40 | .27 | .18 |
| MOTOR/PUMP | .950 | 1.0 | .67 | .45 | .67 | | | | | | | | |
| ACCUMULATOR | .500 | 1.0 | .90 | .85 | .40 | 1 | 1 | .50 | .45 | .43 | .20 | 18 | 17 |
| ELECTRIC MOTOR PUMP | .520 | 1.0 | .82 | .70 | .67 | 1 | 1 | .52 | .43 | .36 | .35 | .29 | 24 |
| VALVE | .250 | 1.0 | .70 | .50 | .67 | 1 | 1 | .25 | .18 | .13 | .17 | .12 | 08 |
| **ACCESSORY GEARBOX** | | | | | | | | | | | | | |
| GEARBOX | .188 | 1.0 | .90 | .85 | .23 | 1 | 33 | 25 | .23 | .21 | .06 | .05 | .05 |
| OVERRUNNING CLUTCH | .074 | 1.0 | .90 | .85 | 1.0 | 1 | 1.00 | 07 | .07 | .06 | .07 | .07 | .06 |
| **DRIVE** | | | | | | | | | | | | | |
| HYDRAULIC MOTOR | .570 | 1.0 | .82 | .70 | .67 | | | | | | | | |
| HYD MOTOR/PUMP | .950 | 1.0 | .67 | .45 | .67 | | | | | | | | |
| ATM | .417 | 1.0 | .90 | .85 | .23 | 1 | .33 | .14 | .12 | .12 | .03 | .03 | .03 |
| **AIR CONDITIONING** | | | | | | | | | | | | | |
| CABIN HEAT VENT SYSTEM | 1.000 | 1.0 | .82 | .70 | .50 | 1 | 1.33 | 1.33 | 1.09 | .93 | .67 | .55 | .47 |
| AVIONICS COOLING SYSTEM | .750 | 1.0 | .82 | .70 | .50 | 1 | 1.33 | 1.00 | .82 | .70 | .50 | .41 | .35 |
| COCKPIT COOLING | 1.050 | 1.0 | .82 | .70 | .50 | 1 | 1.33 | 1.40 | 1.04 | .98 | .70 | .52 | .49 |
| **HYDRAULIC PUMP SYSTEM** | | | | | | | | | | | | | |
| PUMP PACKS | .950 | 1.0 | .67 | .45 | .67 | | 1.33 | 2.53 | 1.69 | 1.14 | 1.69 | 1.13 | .76 |
| PLUMBING & FILTERS | 1.280 | 1.0 | .67 | .45 | .38 | [illegible] | 00 | 1.34 | .90 | .61 | .51 | .34 | .23 |
| CHECK & RELIEF VALVES | .440 | 1.0 | .67 | .45 | .60 | 14 | 00 | 6 16 | 4.13 | 2.77 | 3.70 | 2.48 | 1.66 |
| **ELECTRIC POWER GENERATION** | | | | | | | | | | | | | |
| GENERATORS | .128 | 1.0 | .82 | .70 | 1.0 | 2 | 1.33 | 34 | .28 | .24 | .34 | .28 | .24 |
| CONTROL UNITS | .131 | 1.0 | .56 | .44 | 1.0 | 2 | 1.33 | .35 | .20 | .15 | .35 | .20 | .15 |
| TRANSFORMER-RECTIFIERS | .130 | 1.0 | .82 | .70 | 1.0 | [illegible] | 1.33 | .35 | .28 | .24 | .35 | .28 | .24 |
| SUM OF FAILURE RATES | | | | | | | | 24.0 | 18.0 | 14.1 | | | |

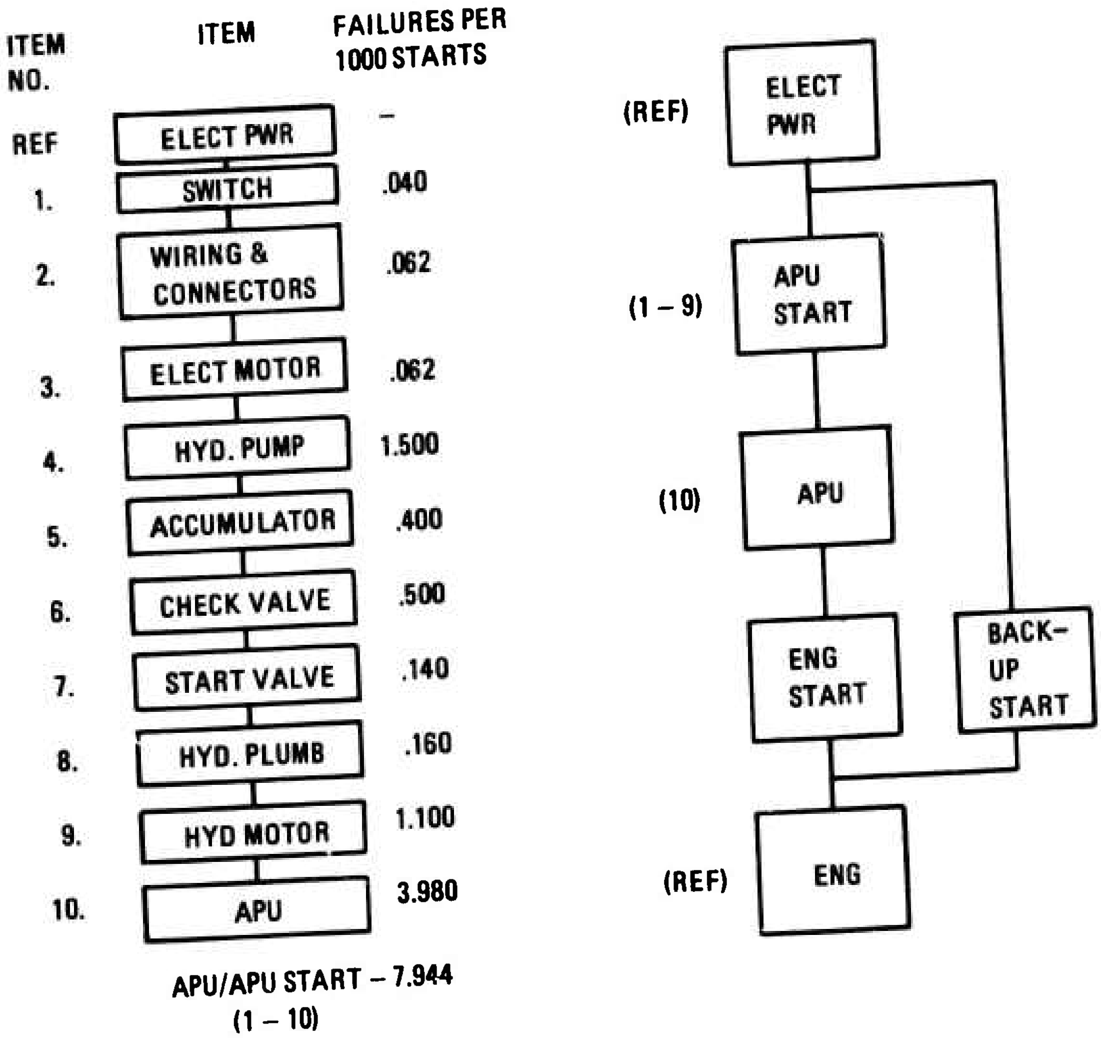
## TABLE XXVIII. SPS COMPONENT FAILURE RATES - CONFIGURATION D

| CONFIGURATION D<br>WITH COCKPIT COOLING, AND WITH BACKUP START | BASE TMR | ADJUSTMENT FACTOR 1970 | ADJUSTMENT FACTOR 1975 | ADJUSTMENT FACTOR 1985 | RATIO MIR TO TMR | QTY PER ACFT | DUTY CYCLE | SYSTEM TMR 1970 | SYSTEM TMR 1975 | SYSTEM TMR 1985 | SYSTEM MIR 1970 | SYSTEM MIR 1975 | SYSTEM MIR 1985 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| <u>ENGINE START SYSTEM</u> | | | | | | | | | | | | | |
| <u>HYDRAULIC</u> | | | | | | | | | | | | | |
| MOTOR | .600 | 1.0 | .67 | .45 | .67 | | | | | | | | |
| VALVE | .250 | 1.0 | .67 | .45 | .60 | | | | | | | | |
| PLUMBING | .650 | 1.0 | .67 | .45 | .38 | | | | | | | | |
| <u>PNEUMATIC</u> | | | | | | | | | | | | | |
| MOTOR | .396 | 1.0 | .82 | .70 | .23 | 1 | 1 | .40 | .33 | .28 | .09 | .08 | .08 |
| VALVE | .225 | 1.0 | .82 | .70 | .60 | 2 | 1 | .45 | .37 | .32 | .27 | .22 | .19 |
| PLUMBING | .027 | 1.0 | .82 | .70 | .40 | 1 | 1 | .03 | .02 | .02 | .01 | .01 | .01 |
| <u>BACKUP START</u> | | | | | | | | | | | | | |
| HYDRAULIC (CONTROL, PACK, PLUMBING) | 2.47 | 1.0 | .82 | .70 | .50 | | | | | | | | |
| <u>PNEUMATIC</u> | | | | | | | | | | | | | |
| CARTRIDGE STARTER | .44 | 1.0 | .82 | .70 | .23 | 1 | 1 | .44 | .36 | .31 | .10 | .08 | .07 |
| CARTRIDGE & CONTROL | .34 | 1.0 | .82 | .70 | .50 | 1 | .004 | .00 | .00 | .00 | .00 | .00 | .00 |
| <u>AUXILIARY POWER PLANT</u> | | | | | | | | | | | | | |
| <u>APU</u> | 5.300 | 1.0 | .82 | .70 | .21 | 1 | 1 | 5.30 | 4.35 | 3.71 | 1.11 | .91 | .78 |
| <u>HYDRAULIC START</u> | | | | | | | | | | | | | |
| MOTOR | .600 | 1.0 | .67 | .45 | .67 | 1 | 1 | .60 | .40 | .27 | .40 | .27 | .18 |
| MOTOR/PUMP | .950 | 1.0 | .67 | .45 | .67 | | | | | | | | |
| ACCUMULATOR | .500 | 1.0 | .90 | .85 | .40 | 1 | 1 | .50 | .45 | .43 | .20 | .18 | .17 |
| ELECTRIC MOTOR PUMP | .520 | 1.0 | .82 | .70 | .67 | 1 | 1 | .52 | .43 | .36 | .35 | .29 | .24 |
| VALVE | .250 | 1.0 | .70 | .50 | .67 | 1 | 1 | .25 | .18 | .13 | .17 | .12 | .08 |
| <u>ACCESSORY GEARBOX</u> | | | | | | | | | | | | | |
| GEARBOX | .188 | 1.0 | .90 | .85 | .23 | 1 | 1.33 | .25 | .23 | .21 | .06 | .05 | .05 |
| OVERRUNNING CLUTCH | .074 | 1.0 | .90 | .85 | 1.0 | 2 | .67 | .10 | .09 | .08 | .10 | .09 | .08 |
| <u>DRIVE</u> | | | | | | | | | | | | | |
| HYDRAULIC MOTOR | .570 | 1.0 | .82 | .70 | .67 | | | | | | | | |
| HYD MOTOR/PUMP | .950 | 1.0 | .67 | .45 | .67 | | | | | | | | |
| ATM | .417 | 1.0 | .90 | .85 | .23 | | | | | | | | |
| <u>AIR CONDITIONING</u> | | | | | | | | | | | | | |
| CABIN HEAT VENT SYSTEM | 1.000 | 1.0 | .82 | .70 | .50 | 1 | 1.33 | 1.33 | 1.09 | .93 | .67 | .55 | .47 |
| AVIONICS COOLING SYSTEM | .750 | 1.0 | .82 | .70 | .50 | 1 | 1.33 | 1.00 | .82 | .70 | .50 | .41 | .35 |
| COCKPIT COOLING | 1.050 | 1.0 | .82 | .70 | .50 | 1 | 1.33 | 1.40 | 1.04 | .98 | .70 | .52 | .49 |
| <u>HYDRAULIC PUMP SYSTEM</u> | | | | | | | | | | | | | |
| PUMP PACKS | .950 | 1.0 | .67 | .45 | .67 | 2 | 1.33 | 2.53 | 1.69 | 1.14 | 1.69 | 1.14 | .76 |
| PLUMBING & FILTERS | 1.280 | 1.0 | .67 | .45 | .38 | .75 | 1.15 | 1.10 | .74 | .50 | .42 | .28 | .19 |
| CHECK & RELIEF VALVES | .440 | 1.0 | .67 | .45 | .60 | 11 | 1.15 | 5.57 | 3.73 | 2.51 | 3.34 | 2.24 | 1.50 |
| <u>ELECTRIC POWER GENERATION</u> | | | | | | | | | | | | | |
| GENERATORS | .128 | 1.0 | .82 | .70 | 1.0 | 2 | 1.33 | .34 | .28 | .24 | .34 | .28 | .24 |
| CONTROL UNITS | .131 | 1.0 | .56 | .44 | 1.0 | 2 | 1.33 | .35 | .28 | .24 | .35 | .28 | .24 |
| TRANSFORMER-RECTIFIERS | .130 | 1.0 | .82 | .70 | 1.0 | 2 | 1.33 | .35 | .20 | .15 | .35 | .20 | .15 |
| SUM OF FAILURE RATES | | | | | | | | 22.8 | 17.1 | 13.5 | | | |

TABLE XXIX. SPS FAILURE RATES

| CONFIG | COCKPIT COOLING | | BACKUP ENGINE START | | SYSTEM FAILURE RATES * | | |
|---|---|---|---|---|---|---|---|
| | WITH | WITHOUT | WITH | WITHOUT | 1970 | 1975 | 1980 |
| A | | X | | X | 28.0 | 20.3 | 15.1 |
| B | | X | | X | 25.9 | 19.1 | 14.2 |
| C | | X | | X | 22.5 | 16.9 | 13.1 |
| D | | X | | X | 21.4 | 16.0 | 12.5 |
| A | | X | X | | 28.3 | 20.3 | 15.2 |
| B | | X | X | | 25.9 | 19.2 | 14.2 |
| C | | X | X | | 22.6 | 16.9 | 13.2 |
| D | | X | X | | 21.4 | 16.0 | 12.5 |
| A | X | | | X | 29.4 | 21.3 | 16.1 |
| B | X | | | X | 27.3 | 20.2 | 15.2 |
| C | X | | | X | 23.9 | 17.9 | 14.1 |
| D | X | | | X | 22.8 | 17.0 | 13.5 |
| A | X | | X | | 29.4 | 21.3 | 16.1 |
| B | X | | X | | 27.3 | 20.2 | 15.2 |
| C | X | | X | | 24.0 | 18.0 | 14.1 |
| D | X | | X | | 22.8 | 17.1 | 13.5 |

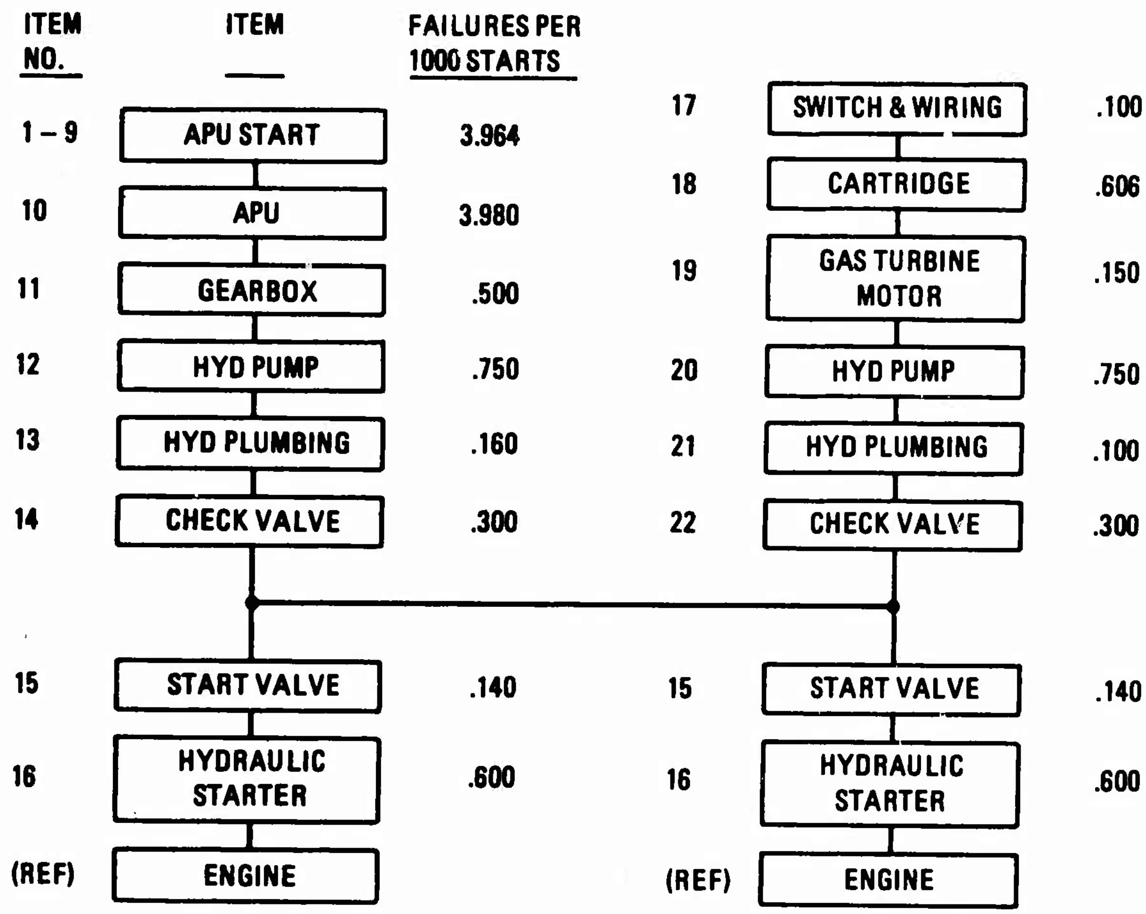
*FAILURES/THOUSAND HOURS




| | | |
|---|---|---|
| APU START (1 – 9) | – | 3.964 F/1000 ST |
| APU | – | 3.980 F/1000 ST |
| APU/APU START | – | 7.944 F/1000 ST |

Figure 37. APU Starting Reliability Analysis.

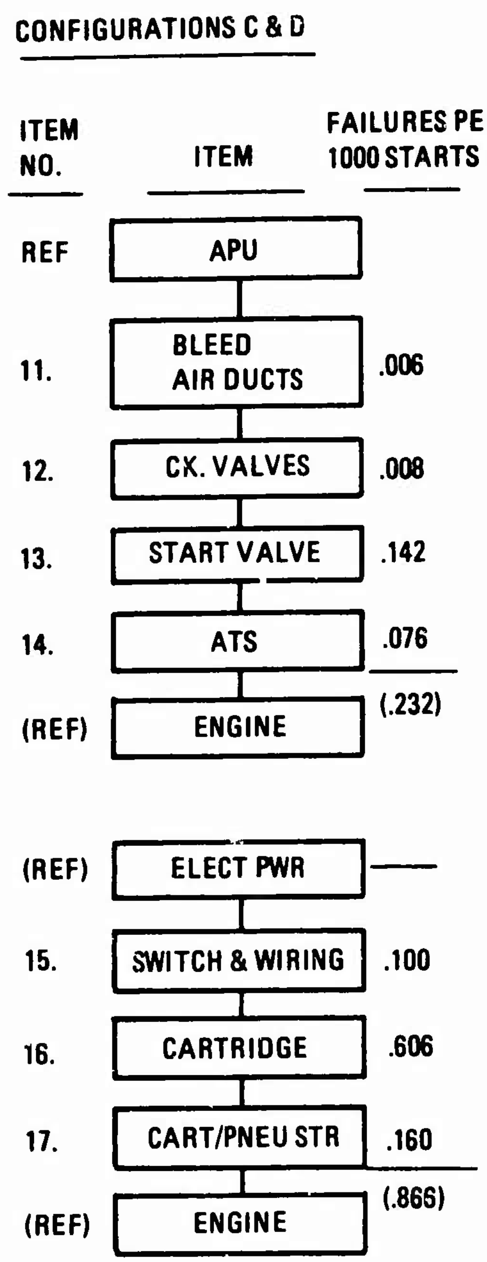
CONFIGURATIONS A & B

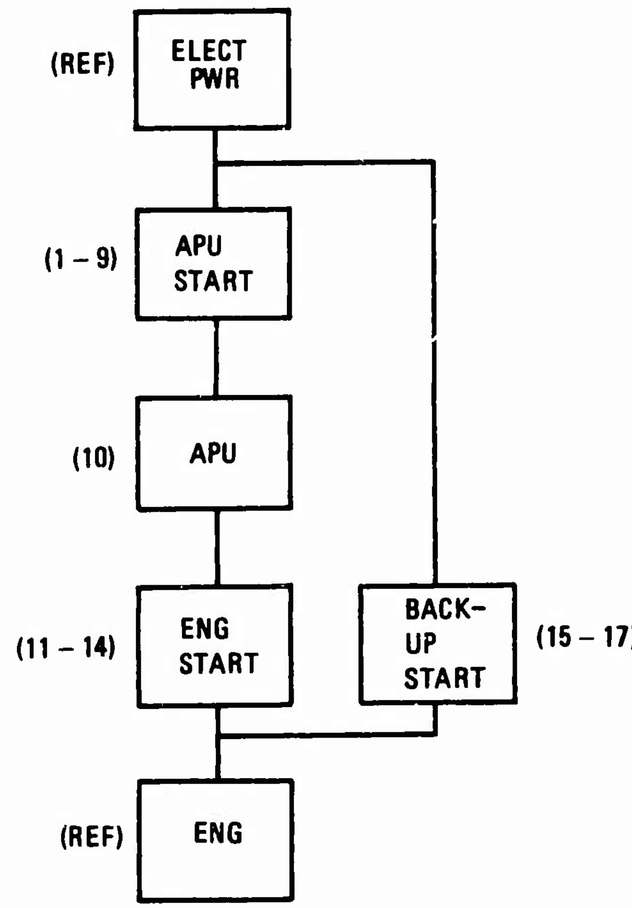



| NORMAL START (1 – 16) | |
|---|---|
| APU HYDRAULIC POWER (1 – 14) | 9.654 |
| HYDRAULIC STARTERS & VALVES (15 – 16) | 1.480 |
| | 11.134 F/1000 STARTS |

| WITH CARTRIDGE BACKUP | |
|---|---|
| PARALLEL 1 – 14 & 17 – 22 | 1.65 |
| STARTERS & VALVE (15 – 16) | 1.48 |
| | 3.13 F/1000 STARTS |

Figure 38. Hydraulic Engine Starting-Reliability Analysis.




NORMAL PNEU START

APU/APU START (1 – 10) – 7.944

ATS START (DUAL) (11 – 14) – .464

8.408 F/1000 STARTS

PNEU START WITH BACKUP
(PARALLEL 1-14 & 15-17)

1.02F/1000 STARTS

Figure 39. Pneumatic Engine Starting - Reliability Analysis.

4. Frequency of maintenance actions, based mainly on failure-rate data developed in the reliability analyses.

From the maintenance analysis, maintenance man-hours per flight hour (MMH/FH) were determined for all SPS components in the baseline system for the three levels of technology, and the summary of SPS MMH/FH is shown in Table XXXI. If cockpit cooling is provided, an additional .005/.045/.036 MMH/FH are estimated for the existing 1975/1985 levels of technology. If backup starting is provided, an incremental .001 MMH/FH is estimated for all levels of technology, primarily for periodic inspection of the cartridge units.

The analysis of life-cycle costs included consideration of items grouped under the headings of research, development, test, and engineering (RDTE); initial investment; and operation and maintenance. Ground rules established for the life-cycle cost analysis included:

| | | |
|---|---|---|
| 1. | Number of Prototypes | 10 |
| 2. | Quantity of Production Aircraft | 2,000 |
| 3. | Contractor Flight Test | Excluded |
| 4. | Customer Flight Test | Excluded |
| 5. | Fatigue Test Article | Excluded |
| 6. | Static Test Article | Excluded |
| 7. | Avionics | Excluded |
| 8. | Maintenance Man-Hours-Org., DS, GS | Table XXXI |
| 9. | Maintenance Man-Hours-Depot | Table XXXI |
| 10. | Peacetime Flying Hours/Year | 500 |
| 11. | Attrition Rates | 5/100,000 F.H. |
| 12. | RDTE Spares | 24 Percent |
| 13. | Initial Spares Percent of Flyaway | Table XXXII |
| 14. | Replenishment Spares Percent of Flyaway | Table XXXII |
| 15. | Crew | Excluded |
| 16. | Fuel | Excluded |

Table XXXII shows SPS spares value factors that were used in the analysis, and Tables XXXIII through XXXVI are breakdowns of non-recurring and recurring costs for subsystems of the SPS. The spares value factors, which are ratios of spares to installed subsystem parameters, were determined from failure rates and an analysis of predicted maintenance and overhaul actions.

TABLE XXX. COMPARATIVE DISPATCH CAPABILITY

| ENGINE START | SPS CONFIGURATION | ENGINE START FAILURES PER THOUSAND STARTS DUE TO SPS FAILURES | | |
|---|---|---|---|---|
| | | 1970 | 1975 | 1985 |
| Hydraulic | A and B | 11.13 | 7.48 | 4.50 |
| Pneumatic | C and D | 8.41 | 6.90 | 5.89 |
| Hydraulic With Backup | A and B | 3.13 | 2.10 | 1.41 |
| Pneumatic With Backup | C and D | .78 | .64 | .55 |

| TABLE XXXI. SPS MAINTENANCE | | | | | | | |
|---|---|---|---|---|---|---|---|
| CONFIGURATION | TECHNOLOGY TIME FRAME | PREVENTIVE MMH PER 1000 FH | CORRECTIVE MMH/1000 FH | | | | TOTAL MMH/ 1000 FH |
| | | | ORG | DS | GS | DEPOT | |
| A | 1970 | 13.54 | 33.78 | 3.10 | 28.35 | 29.97 | 108.74 |
| | 1975 | 13.47 | 25.69 | 1.95 | 18.22 | 23.67 | 83.00 |
| | 1985 | 13.32 | 18.20 | 1.14 | 11.24 | 18.27 | 62.17 |
| B | 1970 | 13.54 | 33.71 | 3.32 | 25.41 | 29.84 | 105.82 |
| | 1975 | 13.47 | 25.61 | 2.12 | 16.35 | 23.56 | 81.11 |
| | 1985 | 13.32 | 18.15 | 1.25 | 10.12 | 18.17 | 61.01 |
| C | 1970 | 13.54 | 30.14 | .84 | 18.05 | 35.32 | 97.89 |
| | 1975 | 13.47 | 23.77 | .60 | 11.75 | 27.82 | 77.41 |
| | 1985 | 13.32 | 17.39 | .39 | 7.41 | 21.47 | 59.98 |
| D | 1970 | 13.54 | 28.40 | 1.15 | 18.15 | 29.84 | 91.08 |
| | 1975 | 13.47 | 22.42 | .85 | 11.84 | 23.56 | 72.14 |
| | 1985 | 13.32 | 16.36 | .59 | 7.48 | 18.17 | 55.92 |

The resulting life-cycle costs are listed in Tables XXXVII through XL, which show comparative costs for the four SPS functional options. The baseline configuration D system with existing technology, which had the lowest life-cycle cost, was selected as the reference against which all the other configurations were compared. For this purpose, a reference value of 100 per cent was assigned to a 1970 technology configuration D system without backup start and cockpit cooling options.

| TABLE XXXII. SPS SPARES VALUE FACTORS | | | |
|---|---|---|---|
| TECHNOLOGY TIME FRAME | SPS CONFIG | INVESTMENT SPARES * | REPLENISHMENT SPARES AND OVERHAUL PARTS (10-YEAR) * |
| 1970 | A | .050 | .120 |
| | B | .040 | .100 |
| | C | .020 | .050 |
| | D | .015 | .040 |
| 1975 | A | .040 | .100 |
| | B | .035 | .070 |
| | C | .020 | .050 |
| | D | .015 | .040 |
| 1985 | A | .040 | .090 |
| | B | .035 | .070 |
| | C | .015 | .040 |
| | D | .015 | .035 |

* RATIO OF SPARES TO INSTALLED SUBSYSTEM VALUES

TABLE XXXIII. SPS COST BREAKDOWN - CONFIGURATION A

| | APU & START | MAIN ENGINE START | ADDITIONAL FOR BACKUP START CAPABILITY | ECS | ADDITIONAL FOR COCKPIT COOLING | AC GENERATOR SYSTEM | FLIGHT HYDRAULIC POWER SYSTEM | AGB | TOTAL | TOTAL EXCLUDING BACKUP START AND COCKPIT COOLING |
|---|---|---|---|---|---|---|---|---|---|---|
| 1970 | | | | | | | | | | |
| Engineering Design, Tooling, and Test, in Percent of Baseline * | 62.1 | 1.4 | 6.2 | 23.2 | 0.3 | 3.6 | 2.0 | 7.1 | 105.9 | **99.4** |
| Prototype Costs, in Percent of Baseline ** | 26.1 | 15.0 | 10.7 | 21.8 | 3.8 | 10.3 | 38.5 | 5.6 | 131.8 | **117.3** |
| Acquisition Cost/Aircraft, in Percent of Baseline *** | 23.1 | 9.0 | 6.2 | 32.3 | 9.2 | 10.8 | 27.7 | 6.2 | 124.7 | **109.3** |
| 1975 | | | | | | | | | | |
| Engineering Design, Tooling, and Test, in Percent of Baseline * | 71.0 | 1.8 | 8.3 | 24.8 | 0.4 | 4.4 | 2.5 | 8.9 | 122.1 | **113.4** |
| Prototype Costs, in Percent of Baseline ** | 33.8 | 19.2 | 11.5 | 23.1 | 4.3 | 12.4 | 47.0 | 6.8 | 158.1 | **142.3** |
| Acquisition Cost/Aircraft, in Percent of Baseline *** | 24.6 | 10.8 | 7.7 | 33.9 | 9.2 | 12.3 | 33.9 | 6.2 | 138.6 | **121.7** |
| 1985 | | | | | | | | | | |
| Engineering Design, Tooling, and Test, in Percent of Baseline * | 79.8 | 2.1 | 10.3 | 26.6 | 0.9 | 5.3 | 3.2 | 10.6 | 138.8 | **127.6** |
| Prototype Costs, in Percent of Baseline ** | 40.6 | 23.1 | 13.7 | 24.4 | 5.6 | 15.0 | 59.8 | 8.5 | 190.7 | **171.4** |
| Acquisition Cost/Aircraft, in Percent of Baseline *** | 29.2 | 16.9 | 6.2 | 35.4 | 10.8 | 13.9 | 53.8 | 7.7 | 173.9 | **156.9** |

* Baseline is engineering design, cooling and test cost for 1970 SPS configuration D, without cockpit cooling and without backup start.

** Baseline is prototype cost for 1970 SPS configuration D, without cockpit cooling and without backup start.

*** Baseline is acquisition cost per aircraft for 1970 SPS configuration D, without cockpit cooling and without backup start.

TABLE XXXIV. SPS COST BREAKDOWN - CONFIGURATION B

| | APU & START | MAIN ENGINE START | ADDITIONAL FOR BACKUP START CAPABILITY | ECS | ADDITIONAL FOR COCKPIT COOLING | AC GENERATOR SYSTEM | FLIGHT HYDRAULIC POWER SYSTEM | AGB | TOTAL | TOTAL EXCLUDING BACKUP START AND COCKPIT COOLING |
|---|---|---|---|---|---|---|---|---|---|---|
| 1970 | | | | | | | | | | |
| Engineering Design, Tooling, and Test, in Percent of Baseline * | 62.1 | 1.4 | 6.2 | 23.2 | 0.3 | 3.6 | 1.8 | 7.1 | 105.7 | 99.2 |
| Prototype Costs, in Percent of Baseline ** | 26.1 | 15.0 | 10.7 | 21.8 | 3.8 | 10.3 | 34.2 | 5.6 | 127.5 | 113.0 |
| Acquisition Cost/Aircraft, in Percent of Baseline *** | 20.0 | 9.2 | 6.2 | 32.3 | 9.2 | 10.8 | 27.7 | 6.2 | 121.6 | 106.2 |
| 1975 | | | | | | | | | | |
| Engineering Design, Tooling, and Test, in Percent of Baseline * | 71.0 | 1.8 | 8.3 | 24.8 | 0.4 | 4.3 | 2.3 | 8.9 | 121.8 | 113.2 |
| Prototype Costs, in Percent of Baseline ** | 33.8 | 19.2 | 11.5 | 23.1 | 4.3 | 12.4 | 42.8 | 6.8 | 153.9 | 138.1 |
| Acquisition Cost/Aircraft, in Percent of Baseline *** | 23.1 | 10.8 | 7.7 | 33.9 | 9.2 | 12.3 | 33.9 | 6.2 | 137.1 | 120.2 |
| 1985 | | | | | | | | | | |
| Engineering Design, Tooling, and Test, in Percent of Baseline * | 79.8 | 2.1 | 10.3 | 26.6 | 0.9 | 5.3 | 3.0 | 10.6 | 138.6 | 127.4 |
| Prototype Costs, in Percent of Baseline ** | 40.6 | 23.1 | 13.7 | 24.4 | 5.6 | 15.0 | 53.4 | 8.5 | 184.3 | 165.0 |
| Acquisition Cost/Aircraft, in Percent of Baseline *** | 27.7 | 16.9 | 6.2 | 35.4 | 10.8 | 13.9 | 53.8 | 7.7 | 172.4 | 155.4 |

* Baseline is engineering design, cooling and test cost for 1970 SPS configuration D, without cockpit cooling and without backup start.

** Baseline is prototype cost for 1970 SPS configuration D, without cockpit cooling and without backup start.

*** Baseline is acquisition cost per aircraft for 1970 SPS configuration D, without cockpit cooling and without backup start.

TABLE XXXV. SPS COST BREAKDOWN - CONFIGURATION C

| | APU & START | MAIN ENGINE START | ADDITIONAL FOR BACKUP START CAPABILITY | ECS | ADDITIONAL FOR COCKPIT COOLING | AC GENERATOR SYSTEM | FLIGHT HYDRAULIC POWER SYSTEM | AGB | TOTAL | TOTAL EXCLUDING BACKUP START AND COCKPIT COOLING |
|---|---|---|---|---|---|---|---|---|---|---|
| **1970** | | | | | | | | | | |
| Engineering Design, Tooling, and Test, in Percent of Baseline * | 62.1 | 2.7 | 5.3 | 23.2 | 0.3 | 3.6 | 1.4 | 8.9 | 107.5 | 101.9 |
| Prototype Costs, in Percent of Baseline ** | 26.1 | 10.4 | 6.7 | 21.8 | 3.8 | 10.3 | 26.1 | 10.3 | 115.5 | 105.0 |
| Acquisition Cost/Aircraft, in Percent of Baseline *** | 20.0 | 10.8 | 4.6 | 32.3 | 9.2 | 10.8 | 21.5 | 9.2 | 118.4 | 104.6 |
| **1975** | | | | | | | | | | |
| Engineering Design, Tooling, and Test, in Percent of Baseline * | 71.0 | 3.5 | 7.1 | 24.8 | 0.4 | 4.4 | 1.8 | 10.6 | 123.6 | 116.1 |
| Prototype Costs, in Percent of Baseline ** | 33.8 | 12.4 | 8.1 | 23.1 | 4.3 | 12.4 | 30.8 | 12.0 | 136.9 | 124.5 |
| Acquisition Cost/Aircraft, in Percent of Baseline *** | 23.1 | 12.3 | 6.2 | 33.9 | 9.2 | 12.3 | 26.2 | 10.8 | 134.0 | 118.6 |
| **1985** | | | | | | | | | | |
| Engineering Design, Tooling, and Test, in Percent of Baseline * | 79.8 | 4.4 | 8.9 | 26.6 | 0.9 | 5.3 | 2.1 | 11.9 | 139.9 | 130.1 |
| Prototype Costs, in Percent of Baseline ** | 40.6 | 15.0 | 10.7 | 24.4 | 5.6 | 15.0 | 36.8 | 14.5 | 162.6 | 146.3 |
| Acquisition Cost/Aircraft, in Percent of Baseline *** | 27.7 | 18.5 | 9.2 | 35.4 | 10.8 | 13.9 | 36.9 | 13.9 | 166.3 | 146.3 |

* Baseline is engineering design, cooling and test cost for 1970 SPS configuration D, without cockpit cooling and without backup start.

** Baseline is prototype cost for 1970 SPS configuration D, without cockpit cooling and without backup start.

*** Baseline is acquisition cost per aircraft for 1970 SPS configuration D, without cockpit cooling and without backup start.

TABLE XXXVI. SPS COST BREAKDOWN - CONFIGURATION D

| | APU & START | MAIN ENGINE START | ADDITIONAL FOR BACKUP START CAPABILITY | ECS | ADDITIONAL FOR COCKPIT COOLING | AC GENERATOR SYSTEM | FLIGHT HYDRAULIC POWER SYSTEM | AGB | TOTAL | TOTAL EXCLUDING BACKUP START AND COCKPIT COOLING |
|---|---|---|---|---|---|---|---|---|---|---|
| **1970** | | | | | | | | | | |
| Engineering Design, Tooling, and Test, in Percent of Baseline * | 62.1 | 2.7 | 5.3 | 23.2 | 0.3 | 3.6 | 1.4 | 6.9 | 105.5 | 100 |
| Prototype Costs, in Percent of Baseline ** | 26.1 | 10.4 | 6.7 | 21.8 | 3.8 | 10.3 | 26.1 | 5.2 | 110.4 | 100 |
| Acquisition Cost/Aircraft, in Percent of Baseline *** | 20.0 | 10.8 | 4.6 | 32.3 | 9.2 | 10.8 | 21.5 | 4.6 | 113.8 | 100 |
| **1975** | | | | | | | | | | |
| Engineering Design, Tooling, and Test, in Percent of Baseline * | 71.0 | 3.5 | 7.1 | 24.8 | 0.4 | 4.4 | 1.8 | 8.2 | 121.2 | 113.7 |
| Prototype Costs, in Percent of Baseline ** | 33.8 | 12.4 | 8.1 | 23.1 | 4.3 | 12.4 | 30.8 | 6.0 | 130.9 | 118.5 |
| Acquisition Cost/Aircraft, in Percent of Baseline *** | 23.1 | 12.3 | 6.2 | 33.9 | 9.2 | 12.3 | 26.2 | 6.1 | 129.3 | 116.9 |
| **1985** | | | | | | | | | | |
| Engineering Design, Tooling, and Test, in Percent of Baseline * | 79.8 | 4.4 | 8.9 | 26.6 | 0.9 | 5.3 | 2.1 | 9.6 | 137.6 | 127.8 |
| Prototype Costs, in Percent of Baseline ** | 40.6 | 15.0 | 10.7 | 24.4 | 5.3 | 15.0 | 36.8 | 6.8 | 154.6 | 138.6 |
| Acquisition Cost/Aircraft, in Percent of Baseline *** | 27.7 | 18.5 | 9.2 | 35.4 | 10.8 | 13.9 | 36.9 | 6.3 | 158.7 | 138.7 |

* Baseline is engineering design, cooling, and test cost for 1970 SPS configuration D, without cockpit cooling and without backup start.

** Baseline is prototype Cost for 1970 SPS configuration D, without cockpit cooling and without backup start.

*** Baseline is acquisition cost per aircraft for 1970 SPS configuration D, without cockpit cooling and without backup start.

TABLE XXXVII. LIFE-CYCLE COSTS - SPS WITHOUT COCKPIT COOLING AND WITHOUT BACKUP ENGINE START

| | CONFIG. A | | | CONFIG. B | | | CONFIG. C | | | CONFIG. D | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1970 | 1975 | 1985 | 1970 | 1975 | 1985 | 1970 | 1975 | 1985 | 1970 | 1975 | 1985 |
| RDT & E | | | | | | | | | | | | |
| ENGINEERING DESIGN | 1.7 | 1.9 | 2.2 | 1.7 | 1.9 | 2.2 | 1.7 | 2.0 | 2.2 | 1.7 | 1.9 | 2.2 |
| TOOLING | 1.1 | 1.3 | 1.5 | 1.1 | 1.3 | 1.5 | 1.1 | 1.3 | 1.5 | 1.1 | 1.3 | 1.5 |
| PROTOTYPES | 1.7 | 2.0 | 2.4 | 1.6 | 2.0 | 2.3 | 1.5 | 1.8 | 2.1 | 1.4 | 1.7 | 2.0 |
| COMPONENT TEST | .6 | .6 | .7 | .6 | .6 | .7 | .6 | .7 | .8 | .6 | .7 | .7 |
| MOCKUPS | .2 | .2 | .2 | .2 | .2 | .2 | .2 | .2 | .2 | .1 | .2 | .2 |
| SYSTEMS MANAGEMENT | .4 | .5 | .6 | .4 | .5 | .6 | .4 | .5 | .6 | .4 | .5 | .6 |
| INITIAL INVESTMENT | | | | | | | | | | | | |
| FLYAWAY COST | 86.1 | 95.7 | 123.7 | 83.6 | 94.5 | 122.3 | 82.4 | 93.3 | 115.1 | 78.7 | 89.6 | 109.0 |
| INITIAL SPARES | 4.3 | 3.8 | 5.0 | 3.3 | 3.3 | 3.7 | 1.6 | 1.9 | 1.8 | 1.2 | 1.3 | 1.6 |
| INITIAL TRAINING & TRAVEL | .1 | .1 | .1 | .1 | .1 | .1 | .1 | .1 | .1 | .1 | .1 | .1 |
| AIRCRAFT - RELATED G.S.E. | 6.4 | 7.1 | 9.1 | 6.2 | 7.0 | 9.1 | 6.1 | 6.9 | 8.5 | 5.8 | 6.8 | 8.1 |
| NON-AIRCRAFT SUPPLIES | .4 | .2 | .2 | .3 | .2 | .2 | .2 | .2 | .2 | .2 | .2 | .2 |
| OPERATIONS & MAINTENANCE | | | | | | | | | | | | |
| REPL. PARTS & DEPOT SPARES | 10.3 | 9.6 | 11.1 | 8.4 | 6.6 | 8.5 | 4.1 | 4.7 | 4.6 | 3.2 | 3.6 | 3.8 |
| DIRECT MAINTENANCE LABOR | .7 | .5 | .4 | .7 | .5 | .4 | .5 | .4 | .3 | .5 | .4 | .3 |
| DEPOT LABOR | 2.3 | 1.8 | 1.4 | 2.3 | 1.8 | 1.4 | 2.8 | 2.2 | 1.7 | 2.3 | 1.8 | 1.4 |
| INDIRECT MAINTENANCE | .2 | .2 | .1 | .2 | .2 | .1 | .2 | .2 | .1 | .2 | .1 | .1 |
| REPL. TRAINING & TRAVEL | .8 | .6 | .4 | .9 | .7 | .5 | .7 | .5 | .4 | .7 | .5 | .4 |
| SUPPORT PERS. PAY & ALLOW. | 1.2 | .9 | .7 | 1.3 | 1.0 | .7 | 1.0 | .8 | .6 | 1.0 | .8 | .6 |
| MEDICAL & ARMY-WIDE | .8 | .6 | .4 | .9 | .6 | .5 | .6 | .5 | .4 | .6 | .5 | .4 |
| TOTAL SYSTEM COST | 119.1 | 127.7 | 160.3 | 113.9 | 123.0 | 154.8 | 102.2 | 117.3 | 147.1 | 100.0 | 111.9 | 133.1 |

*Costs shown in percent of total system cost for 1970 SPS configuration D without cockpit cooling and without backup start.

TABLE XXXVIII. LIFE-CYCLE COSTS - SPS WITH COCKPIT COOLING AND WITHOUT BACKUP ENGINE START

| | CONFIG. A | | | CONFIG. B | | | CONFIG. C | | | CONFIG. D | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1970 | 1975 | 1985 | 1970 | 1975 | 1985 | 1970 | 1975 | 1985 | 1970 | 1975 | 1985 |
| <u>RDT & E</u> | | | | | | | | | | | | |
| ENGINEERING DESIGN | 1.7 | 1.9 | 2.2 | 1.7 | 1.9 | 2.2 | 1.7 | 2.0 | 2.2 | 1.7 | 2.1 | 2.2 |
| TOOLING | 1.1 | 1.3 | 1.5 | 1.1 | 1.3 | 1.5 | 1.2 | 1.3 | 1.5 | 1.1 | 1.3 | 1.5 |
| PROTOTYPES | 1.7 | 2.1 | 2.5 | 1.7 | 2.0 | 2.4 | 1.5 | 1.8 | 2.2 | 1.5 | 1.7 | 2.0 |
| COMPONENT TEST | .6 | .6 | .7 | .6 | .6 | .7 | .6 | .7 | .7 | .6 | .7 | .7 |
| MOCKUPS | .2 | .2 | .3 | .2 | .2 | .3 | .2 | .2 | .2 | .1 | .2 | .2 |
| SYSTEMS MANAGEMENT | .5 | .5 | .6 | .4 | .5 | .6 | .4 | .5 | .6 | .4 | .5 | .6 |
| <u>INITIAL INVESTMENT</u> | | | | | | | | | | | | |
| FLYAWAY COST | 93.3 | 103.0 | 132.0 | 90.8 | 104.2 | 132.0 | 89.7 | 101.8 | 118.8 | 86.0 | 96.9 | 117.5 |
| INITIAL SPARES | 4.7 | 4.1 | 5.3 | 3.6 | 3.6 | 3.9 | 1.8 | 2.1 | 1.8 | 1.3 | 1.4 | 1.8 |
| INITIAL TRAINING & TRAVEL | .1 | .1 | .1 | .1 | .1 | .1 | .1 | .1 | .1 | .1 | .1 | .1 |
| AIRCRAFT - RELATED GSE | 6.3 | 7.6 | 9.8 | 6.7 | 7.7 | 9.8 | 6.7 | 7.5 | 8.8 | 6.4 | 7.1 | 8.7 |
| NON-AIRCRAFT SUPPLIES | .4 | .3 | .2 | .3 | .3 | .2 | .3 | .2 | .2 | .3 | .2 | .2 |
| <u>OPERATIONS & MAINTENANCE</u> | | | | | | | | | | | | |
| REPL. PARTS & DEPOT SPARES | 11.2 | 10.3 | 11.9 | 9.1 | 7.3 | 9.2 | 4.5 | 5.1 | 4.8 | 3.4 | 3.9 | 4.1 |
| DIRECT MAINTENANCE LABOR | .7 | .5 | .4 | .7 | .5 | .4 | .5 | .4 | .3 | .5 | .4 | .3 |
| DEPOT LABOR | 2.4 | 1.8 | 1.4 | 2.4 | 1.8 | 1.4 | 2.9 | 2.2 | 1.7 | 2.4 | 1.8 | 1.4 |
| INDIRECT MAINTENANCE | .2 | .2 | .1 | .2 | .2 | .1 | .2 | .1 | .1 | .2 | .1 | .1 |
| REPL. TRAINING & TRAVEL | .8 | .6 | .5 | .9 | .7 | .5 | .7 | .5 | .4 | .7 | .5 | .4 |
| SUPPORT PERS. PAY & ALLOW. | 1.2 | .9 | .7 | 1.3 | 1.0 | .7 | 1.0 | .8 | .6 | 1.0 | .8 | .6 |
| MEDICAL & ARMY-WIDE | .8 | .6 | .4 | .9 | .6 | .5 | .6 | .5 | .4 | .6 | .5 | .4 |
| TOTAL SYSTEM COST | 128.2 | 136.5 | 170.3 | 122.8 | 134.9 | 166.3 | 114.3 | 123.0 | 145.1 | 108.2 | 120.3 | 142.8 |

*Costs shown in percent of total system cost for 1970 SPS configuration D without cockpit cooling and without backup start.

TABLE XXXIX. LIFE-CYCLE COSTS - SPS WITHOUT COCKPIT COOLING AND WITH BACKUP ENGINE START

| | CONFIG. A | | | CONFIG. B | | | CONFIG. C | | | CONFIG. D | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1970 | 1975 | 1985 | 1970 | 1975 | 1985 | 1970 | 1975 | 1985 | 1970 | 1975 | 1985 |
| RDT & E | | | | | | | | | | | | |
| ENGINEERING DESIGN | 1.8 | 2.1 | 2.4 | 1.8 | 2.1 | 2.4 | 1.8 | 2.1 | 2.4 | 1.5 | 2.1 | 2.3 |
| TOOLING | 1.2 | 1.4 | 1.6 | 1.2 | 1.4 | 1.6 | 1.2 | 1.4 | 1.6 | 1.2 | 1.4 | 1.6 |
| PROTOTYPES | 1.8 | 2.2 | 2.6 | 1.8 | 2.1 | 2.6 | 1.6 | 1.9 | 2.2 | 1.5 | 1.8 | 2.1 |
| COMPONENT TEST | .6 | .7 | .8 | .6 | .7 | .8 | .6 | .7 | .8 | .6 | .7 | .8 |
| MOCKUPS | .2 | .2 | .3 | .2 | .2 | .3 | .2 | .2 | .2 | .2 | .2 | .2 |
| SYSTEMS MANAGEMENT | .5 | .6 | .7 | .5 | .6 | .7 | .5 | .5 | .6 | .4 | .5 | .6 |
| INITIAL INVESTMENT | | | | | | | | | | | | |
| FLYAWAY COST | 90.8 | 101.8 | 127.2 | 88.4 | 101.8 | 127.2 | 86.0 | 98.1 | 117.5 | 84.4 | 94.5 | 116.2 |
| INITIAL SPARES | 4.5 | 4.1 | 5.1 | 3.5 | 3.6 | 3.8 | 1.7 | 1.9 | 1.8 | 1.22 | 1.4 | 1.8 |
| INITIAL TRAINING & TRAVEL | .1 | .1 | .1 | .1 | .1 | .1 | .1 | .1 | .1 | .1 | .1 | .1 |
| AIRCRAFT - RELATED GSE | 6.7 | 7.5 | 9.4 | 6.5 | 7.5 | 9.4 | 6.4 | 7.3 | 8.7 | 6.1 | 7.0 | 8.6 |
| NON-AIRCRAFT SUPPLIES | .4 | .3 | .2 | .3 | .2 | .2 | .3 | .2 | .2 | .2 | .2 | .2 |
| OPERATIONS & MAINTENANCE | | | | | | | | | | | | |
| REPL. PARTS & DEPOT SPARES | 10.9 | 10.2 | 11.5 | 8.9 | 7.1 | 8.9 | 4.3 | 4.9 | 4.7 | 3.3 | 3.8 | 4.1 |
| DIRECT MAINTENANCE LABOR | .7 | .5 | .4 | .7 | .5 | .4 | .5 | .4 | .3 | .5 | .4 | .3 |
| DEPOT LABOR | 2.4 | 1.9 | 1.4 | 2.4 | 1.9 | 1.4 | 2.9 | 2.2 | 1.7 | 2.4 | 1.9 | 1.4 |
| INDIRECT MAINTENANCE | .2 | .2 | .1 | .2 | .2 | .1 | .2 | .1 | .1 | .2 | .1 | .1 |
| REPL. TRAINING & TRAVEL | .8 | .6 | .5 | .9 | .7 | .5 | .7 | .5 | .4 | .7 | .5 | .4 |
| SUPPORT PERS. PAY & ALLOW. | 1.2 | .9 | .7 | 1.4 | 1.0 | .7 | 1.0 | .8 | .6 | 1.0 | .8 | .5 |
| MEDICAL & ARMY-WIDE | .8 | .6 | .4 | .9 | .6 | .5 | .6 | .5 | .4 | .6 | .5 | .4 |
| TOTAL SYSTEM COST | 125.7 | 141.6 | 165.1 | 120.2 | 132.2 | 166.4 | 110.5 | 124.0 | 144.4 | 104.2 | 117.9 | 142.0 |

*Costs shown in percent of total system cost for 1970 SPS configuration D without cockpit cooling and without backup start.

**TABLE XL. LIFE-CYCLE COSTS - SPS WITH COCKPIT COOLING AND WITH BACKUP ENGINE START**

| | CONFIG. A | | | CONFIG. B | | | CONFIG. C | | | CONFIG. D | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1970 | 1975 | 1985 | 1970 | 1975 | 1985 | 1970 | 1975 | 1985 | 1970 | 1975 | 1985 |
| **RDT & E** | | | | | | | | | | | | |
| ENGINEERING DESIGN | 1.8 | 2.1 | 2.4 | 1.8 | 2.1 | 2.4 | 1.8 | 2.1 | 2.4 | 1.8 | 2.1 | 2.4 |
| TOOLING | 1.2 | 1.4 | 1.6 | 1.2 | 1.4 | 1.6 | 1.2 | 1.4 | 1.6 | 1.2 | 1.4 | 1.8 |
| PROTOTYPES | 1.9 | 2.2 | 2.7 | 1.8 | 2.2 | 2.6 | 1.6 | 1.9 | 2.3 | 1.6 | 1.9 | 2.2 |
| COMPONENT TEST | .6 | .7 | .8 | .6 | .7 | .8 | .6 | .7 | .8 | .6 | .7 | .9 |
| MOCKUPS | .1 | .2 | .3 | .2 | .2 | .3 | .2 | .2 | .2 | .2 | .2 | .2 |
| SYSTEMS MANAGEMENT | .5 | .6 | .7 | .5 | .6 | .7 | .5 | .5 | .6 | .5 | .5 | .6 |
| **INITIAL INVESTMENT** | | | | | | | | | | | | |
| FLYAWAY COST | 98.1 | 109.0 | 135.6 | 95.7 | 110.2 | 136.9 | 93.3 | 106.6 | 126.0 | 89.7 | 101.8 | 124.8 |
| INITIAL SPARES | 4.9 | 4.4 | 5.5 | 3.8 | 3.9 | 4.1 | 1.9 | 2.1 | 1.9 | 1.3 | 1.5 | 1.9 |
| INITIAL TRAINING & TRAVEL | .1 | .1 | .1 | .1 | .1 | .1 | .1 | .1 | .1 | .1 | .1 | .1 |
| AIRCRAFT - RELATED G.S.E. | 7.3 | 8.1 | 10.0 | 7.1 | 8.2 | 10.1 | 6.9 | 7.9 | 9.3 | 6.7 | 7.5 | 9.2 |
| NON-AIRCRAFT SUPPLIES | .4 | .3 | .2 | .3 | .2 | .2 | .3 | .2 | .2 | .3 | .2 | .2 |
| **OPERATIONS & MAINTENANCE** | | | | | | | | | | | | |
| REPL. PARTS & DEPOT SPARES | 11.8 | 10.9 | 12.2 | 9.57 | 7.7 | 9.6 | 4.7 | 5.3 | 5.0 | 3.6 | 4.1 | 4.4 |
| DIRECT MAINTENANCE LABOR | .7 | .5 | .4 | .7 | .5 | .4 | .6 | .4 | .4 | .6 | .4 | .3 |
| DEPOT LABOR | 2.4 | 1.9 | 1.5 | 2.4 | 1.9 | 1.5 | 2.9 | 2.2 | 1.7 | 2.4 | 1.9 | 1.5 |
| INDIRECT MAINTENANCE | .2 | .2 | .1 | .2 | .2 | .1 | .2 | .1 | .1 | .2 | .1 | .1 |
| REPL. TRAINING & TRAVEL | .8 | .6 | .5 | .9 | .7 | .5 | .7 | .5 | .4 | .7 | .5 | .4 |
| SUPPORT PERS. PAY & ALLOW. | 1.2 | .9 | .7 | 1.4 | 1.0 | .7 | 1.0 | .8 | .6 | 1.0 | .8 | .6 |
| MEDICAL & ARMY-WIDE | .8 | .6 | .4 | .9 | .6 | .5 | .7 | .5 | .4 | .7 | .5 | .4 |
| TOTAL SYSTEM COST | 135.0 | 144.6 | 175.4 | 129.1 | 142.3 | 173.0 | 119.0 | 134.4 | 154.1 | 112.9 | 126.2 | 151.9 |

*Costs shown in percent of total system cost for 1970 SPS configuration D without cockpit cooling and without backup start.

## SPS COMPARISON PARAMETER RANKING

To determine the relative importance of each of the thirteen parameters which were the basis of the evaluation of candidate systems, the chart in Table XLI was developed. Each parameter was compared with successive parameters, one by one. If a parameter was judged to be more important than another in evaluating the SPS, then the first parameter was rated 1 and the other parameter was rated 0. For example, the effect of the SPS on aircraft system complexity was judged to be more important than system integration complexity, so the effect on aircraft system complexity was scored 1 and system integration complexity was scored 0. After 78 such comparisons were accomplished, the scores were added, and the relative scores for each of the 13 parameters were a a direct reflection of their relative importance in evaluating the SPS. The ranking of each of these parameters in order of importance was included in Table XLI. These scores were carefully considered in determining weighting factors to use in the succeeding system trade-off study.

As in previous trade-off studies, the 13 parameters which were the basis of the evaluation were divided into a weight group, a cost group, and a safety/reliability group, which were assumed to be of approximately equal importance in evaluating the candidate secondary power system (Table XLII). Accordingly, the 13 parameters were separated into their respective groups and were assigned weighting factors which closely corresponded to the final scores defined in Table XLII. These weighting factors then were a measure of the relative importance of each parameter, and the desired equality of the weight, cost, and safety/reliability groups was essentially preserved. The candidate systems would impact on aircraft complexity both in terms of weight and cost, and so the weighting factor for influence on aircraft complexity in Table XLII was equally divided between the weight and body groups.

## SPS TRADE-OFF EVALUATION RESULTS

The comparative evaluation of secondary power systems is summarized in Tables XLII through XLVI, which are applicable to the various functional options as follows:

1. Table XLIII – baseline SPS without cockpit ECS cooling or backup engine starting

## TABLE XLI. SPS COMPARISON PARAMETER RANKING

| | | | | | | | | | | | | | TOTAL WEIGHT | RANK |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| EFFECT ON AIRCRAFT SYSTEM COMPLEXITY | 110011100011 | | | | | | | | | | | | 7 | 6 |
| SYSTEM INTEGRATION COMPLEXITY | 0 | 00011101011 | | | | | | | | | | | 6 | 8 |
| SECONDARY POWER SYSTEM COMPLEXITY | 0 | 1 | 0011100011 | | | | | | | | | | 6 | 7 |
| TAKE OFF WT INFLUENCE (GROSS WT) | 1 | 1 | 1 | 111111111 | | | | | | | | | 12 | 1 |
| SYSTEM WEIGHT | 1 | 1 | 1 | 0 | 11111111 | | | | | | | | 11 | 2 |
| RANGE INFLUENCE | 0 | 0 | 0 | 0 | 0 | 1100001 | | | | | | | 3 | 10 |
| POWER REQUIREMENTS | 0 | 0 | 0 | 0 | 0 | 0 | 100001 | | | | | | 2 | 11 |
| SYSTEM VOLUME | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 00001 | | | | | 1 | 12 |
| SYSTEM RELIABILITY | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 1011 | | | | 9 | 4 |
| DISPATCH AVAILABILITY | 1 | 0 | 1 | 0 | 0 | 1 | 1 | 1 | 0 | 011 | | | 7 | 5 |
| SPS LIFE – CYCLE COST | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 11 | | 10 | 3 |
| SYSTEM MAINTAINABILITY | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 4 | 9 |
| SYSTEM VULNERABILITY | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 13 |

| TABLE XLII. WEIGHTING FACTORS FOR SPS EVALUATION | Rank | Weighting Factor | Summation |
|---|---|---|---|
| **Weight Group** | | | |
| Influence on Aircraft TOGW | 1 | 13 | |
| SPS Weight | 2 | 13 | |
| 1/2 of Influence on Aircraft Complexity | 6 | 4 | |
| SPS Volume | 12 | 4 | |
| Sum of Weight Group | | | 34 |
| **Cost Group** | | | |
| SPS Life-Cycle Cost | 3 | 10 | |
| 1/2 of Influence on Aircraft Complexity | 6 | 4 | |
| SPS Integration Complexity | 8 | 8 | |
| SPS Maintainability | 9 | 4 | |
| Influence on Aircraft Range | 10 | 4 | |
| Power Requirements | 11 | 4 | |
| Sum of Cost Group | | | 34 |
| **Safety-Reliability Group** | | | |
| SPS Reliability | 4 | 10 | |
| Dispatch Availability | 5 | 10 | |
| SPS Complexity | 7 | 8 | |
| Vulnerability | 13 | 4 | |
| Sum of Safety/Reliability Group | | | 32 |
| TOTAL | | | 100 |

2. Table XLIV - SPS with cockpit ECS cooling but without backup engine starting

3. Table XLV - SPS with engine backup starting but without cockpit ECS cooling

4. Table XLVI - SPS with both cockpit ECS cooling and backup engine starting

ECS cockpit cooling is refrigeration cooling for the cockpit. In all cases, a cabin heating and ventilation system is provided; if ECS cooling is not provided for the cockpit, the cabin heating and ventilating unit supplies that service to the cockpit.

The tables list numerical values for each of the 13 parameters which are the basis for SPS evaluation, for each of three levels of technology - existing (1970), 1975 and 1985. Also listed are the comparative ratings for configurations A, B, C, and D for each level of technology. Where the parameters have been quantified (weight, volume, cost, reliability, maintainability), the comparative ratings are directly related to the numerical values of the parameters. In other cases, the weighted ratings reflect a judgment of the relative goodness of one configuration compared to another.

The system selected as the optimum SPS had the APU driving directly into the AGB, with overrunning clutches to isolate the APU and the rotor transmission. Pneumatic starter motors were mounted on each main engine, with the necessary pneumatic plumbing. The superiority of this system configuration over the other configurations was attributed to superiority in weight, cost, reliability, and maintainability.

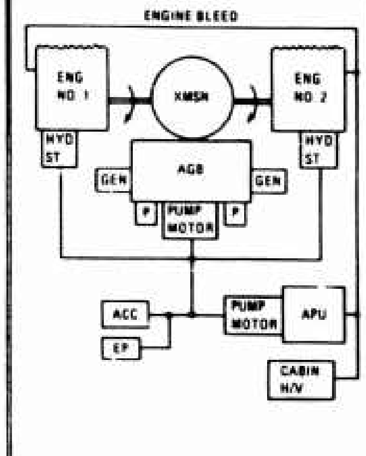
Each evaluation parameter is discussed individually below.

SPS Weight

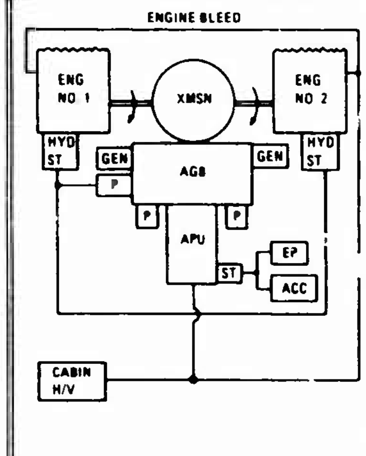
SPS weights include weights of components and installation hardware, which have been developed previously. SPS configuration D is the lightest system for each level of technology and each functional option. Considering 1970 technology, the baseline system weighs 465 pounds, backup starting involves a penalty of 25 pounds, and cockpit ECS adds 32 pounds to the system.

# TABLE XLIII. COMPARATIVE EVALUATION CHART FOR SPS WITHOUT COCKPIT COOLING & WITHOUT BACKUP START

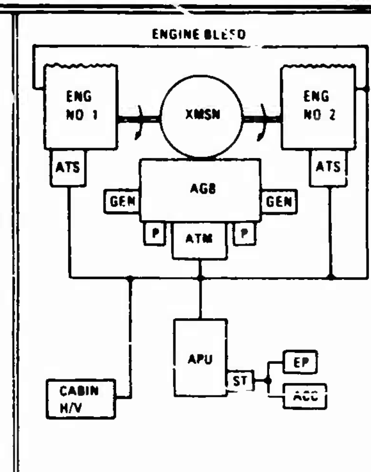
- ACC — HYD ACCUMULATOR
- AGB — ACCESSORY GEARBOX
- ATM — AIR TURBINE MOTOR
- ATS — AIR TURBINE STARTER
- CHP — CART - HYD PUMP
- CPS — CART PNEU STARTER
- ECS — ENVIRONMENT CONTROL SYSTEM
- ENG — ENGINE
- EP — ELECTRIC MOTOR PUMP
- GEN — AC GENERATOR
- HYD ST — HYDRAULIC STARTER
- P — HYDRAULIC PUMP
- XMSN — TRANSMISSION



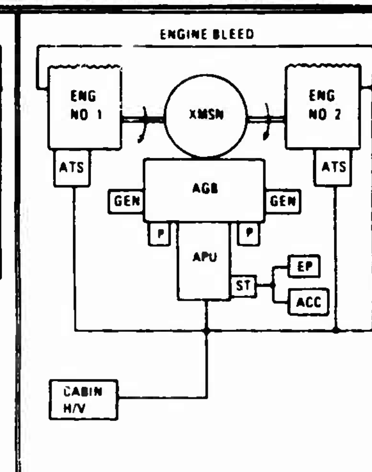

CONFIG A




CONFIG B




CONFIG C




CONFIG D

**CONFIG A**

| PARAMETER | WT FACTOR | 1970 | 1975 | 1985 | RATING 1970 | RATING 1975 | RATING 1985 |
|---|---|---|---|---|---|---|---|
| WEIGHT, COMPONENT & INSTL (LBS) | 13 | 484.1 | 397.6 | 335.7 | 12.5 | 12.7 | 12.8 |
| TOGW INFLUENCF (LB) (2.07) GROWTH FACTOR | 13 | 1050.8 | 856.2 | 719.8 | 11.8 | 12.1 | 12.3 |
| 10 YR LIFE CYCLE COST PERCENT OF BASELINE | 10 | 119 | 128 | 160 | 8.1 | 8.8 | 8.0 |
| SPS RELIABILITY (FAILURES/1000 FLT HRS) | 10 | 28.0 | 20.3 | 15.1 | 6.9 | 7.3 | 7.8 |
| DISPATCH AVAILABILITY (FAILURES/1000 STARTS) | 10 | 11.1 | 8.1 | 6.0 | 6.8 | 8.3 | 9.8 |
| EFFECT ON AIRCRAFT COMPLEXITY | 8 | 2 | 2 | 2 | 7 | 7 | 7 |
| SPS COMPLEXITY | 8 | 4 | 4 | 4 | 5 | 5 | 5 |
| INTEGRATION COMPLEXITY | 8 | 1 | 1 | 1 | 8 | 8 | 8 |
| MAINTAINABILITY (MMH/1000 FLT HRS) | 4 | 102.7 | 77.5 | 57.8 | 3.2 | 3.3 | 3.5 |
| RANGE INFLUENCE (MILES) | 4 | 2.9 | 1.9 | 1.5 | 3.4 | 3.5 | 3.7 |
| PWR RQMTS (HP) | 4 | 76 | 74 | 71 | 3.4 | 3.4 | 3.4 |
| VOLUME | 4 | 3938 | 3723 | 3268 | 4.0 | 4.0 | 4.0 |
| VULNERABILITY | 4 | 2 | 2 | 2 | 3.5 | 3.5 | 3.5 |
| TOTAL SCORE | | | | | 83.6 | 86.7 | 88.3 |
| RANKING | | | | | 4 | 4 | 4 |

**CONFIG B**

| PARAMETER | 1970 | 1975 | 1985 | RATING 1970 | RATING 1975 | RATING 1985 |
|---|---|---|---|---|---|---|
| WEIGHT, COMPONENT & INSTL (LBS) | 481.0 | 400.0 | 343.0 | 12.6 | 12.6 | 12.5 |
| TOGW INFLUENCF (LB) (2.07) GROWTH FACTOR | 995.0 | 828.0 | 710.0 | 12.6 | 12.6 | 12.5 |
| 10 YR LIFE CYCLE COST PERCENT OF BASELINE | 114 | 123 | 156 | 8.6 | 9.0 | 8.4 |
| SPS RELIABILITY (FAILURES/1000 FLT HRS) | 25.9 | 19.1 | 14.2 | 7.9 | 8.0 | 8.6 |
| DISPATCH AVAILABILITY (FAILURES/1000 STARTS) | 11.1 | 8.1 | 6.0 | 6.8 | 8.3 | 9.8 |
| EFFECT ON AIRCRAFT COMPLEXITY | 1 | 1 | 1 | 8 | 8 | 8 |
| SPS COMPLEXITY | 2 | 2 | 2 | 7 | 7 | 7 |
| INTEGRATION COMPLEXITY | 2 | 2 | 2 | 7 | 7 | 7 |
| MAINTAINABILITY (MMH/1000 FLT HRS) | 99.8 | 75.8 | 56.8 | 3.3 | 3.5 | 3.6 |
| RANGE INFLUENCE (MILES) | [illegible] | 1.7 | 1.4 | 4 | 4 | 4 |
| PWR RQMTS (HP) | 66 | 64 | 62 | 4 | 4 | 4 |
| VOLUME | 3943 | 3765 | 3287 | 4 | 4 | 4 |
| VULNERABILITY | 1 | 1 | 1 | 4 | 4 | 4 |
| TOTAL SCORE | | | | 89.8 | 92.0 | 93.4 |
| RANKING | | | | 2 | 2 | 2 |

**CONFIG C**

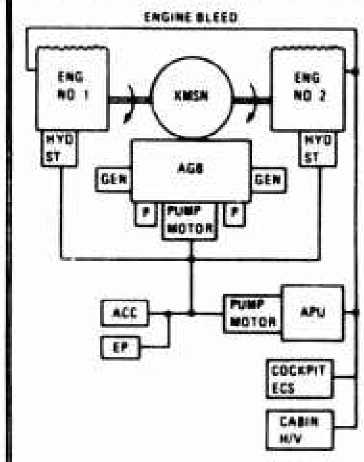
| PARAMETER | 1970 | 1975 | 1985 | RATING 1970 | RATING 1975 | RATING 1985 |
|---|---|---|---|---|---|---|
| WEIGHT, COMPONENT & INSTL (LBS) | 480.7 | 398.5 | 338.7 | 12.6 | 12.6 | 12.7 |
| TOGW INFLUENCF (LB) (2.07) GROWTH FACTOR | 1043.8 | 856.2 | 723.8 | 11.9 | 12.1 | 12.3 |
| 10 YR LIFE CYCLE COST PERCENT OF BASELINE | 102 | 117 | 147 | 9.8 | 9.5 | 9.0 |
| SPS RELIABILITY (FAILURES/1000 FLT HRS) | 22.5 | 16.9 | 13.1 | 9.5 | 9.5 | 9.5 |
| DISPATCH AVAILABILITY (FAILURES/1000 STARTS) | 8.4 | 6.9 | 5.9 | 10.0 | 10.0 | 10.0 |
| EFFECT ON AIRCRAFT COMPLEXITY | 2 | 2 | 2 | 7 | 7 | 7 |
| SPS COMPLEXITY | 3 | 3 | 3 | 6 | 6 | 6 |
| INTEGRATION COMPLEXITY | 1 | 1 | 1 | 8 | 8 | 8 |
| MAINTAINABILITY (MMH/1000 FLT HRS) | 91.9 | 71.9 | 55.6 | 3.7 | 3.7 | 3.7 |
| RANGE INFLUENCE (MILES) | 3.2 | 2.2 | 1.7 | 2.9 | 2.8 | 3.1 |
| PWR RQMTS (HP) | 86 | 82 | 78 | 2.8 | 2.9 | 3.0 |
| VOLUME | 5864 | 5630 | 5181 | 2.0 | 1.9 | 1.7 |
| VULNERABILITY | 2 | 2 | 2 | 3.5 | 3.5 | 3.5 |
| TOTAL SCORE | | | | 89.7 | 89.5 | 89.5 |
| RANKING | | | | 3 | 3 | 3 |

**CONFIG D**

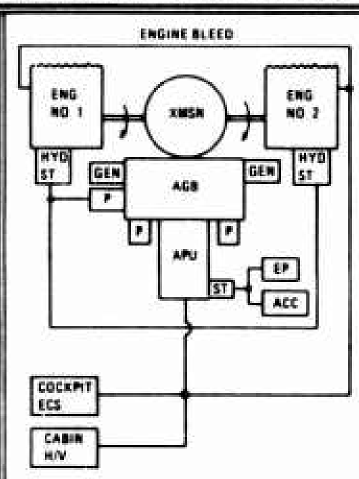
| PARAMETER | 1970 | 1975 | 1985 | RATING 1970 | RATING 1975 | RATING 1985 |
|---|---|---|---|---|---|---|
| WEIGHT, COMPONENT & INSTL (LBS) | 465.4 | 387.5 | 330.5 | 13 | 13 | 13 |
| TOGW INFLUENCF (LB) (2.07) GROWTH FACTOR | 963.0 | 802.0 | 684.0 | 13 | 13 | 13 |
| 10 YR LIFE CYCLE COST PERCENT OF BASELINE | 100 | 112 | 133 | 10 | 10 | 10 |
| SPS RELIABILITY (FAILURES/1000 FLT HRS) | 21.4 | 16.0 | 12.5 | 10 | 10 | 10 |
| DISPATCH AVAILABILITY (FAILURES/1000 STARTS) | 8.4 | 6.9 | 5.9 | 10 | 10 | 10 |
| EFFECT ON AIRCRAFT COMPLEXITY | 1 | 1 | 1 | 8 | 8 | 8 |
| SPS COMPLEXITY | 1 | 1 | 1 | 8 | 8 | 8 |
| INTEGRATION COMPLEXITY | 2 | 2 | 2 | 7 | 7 | 7 |
| MAINTAINABILITY (MMH/1000 FLT HRS) | 85.1 | 66.6 | 51.5 | 4 | 4 | 4 |
| RANGE INFLUENCE (MILES) | 2.5 | 1.7 | 1.4 | 4 | 4 | 4 |
| PWR RQMTS (HP) | 66 | 64 | 62 | 4 | 4 | 4 |
| VOLUME | 4866 | 4642 | 4192 | 3.1 | 3.0 | 2.9 |
| VULNERABILITY | 1 | 1 | 1 | 4 | 4 | 4 |
| TOTAL SCORE | | | | 98.1 | 98.0 | 97.9 |
| RANKING | | | | 1 | 1 | 1 |

# TABLE XLIV. COMPARATIVE EVALUATION CHART FOR SPS WITH COCKPIT COOLING AND WITHOUT BACKUP ENGINE START

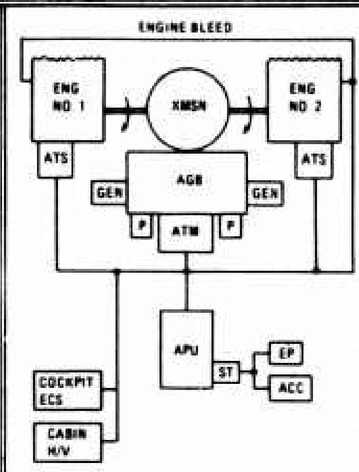
| Symbol | Meaning |
|---|---|
| ACC | HYD ACCUMULATOR |
| AGB | ACCESSORY GEARBOX |
| ATM | AIR TURBINE MOTOR |
| ATS | AIR TURBINE STARTER |
| CHP | CART - HYD PUMP |
| CPS | CART - PNEU STARTER |
| ECS | ENVIRONMENT CONTROL SYSTEM |
| ENG | ENGINE |
| EP | ELECTRIC MOTOR PUMP |
| GEN | AC GENERATOR |
| HYD ST | HYDRAULIC STARTER |
| P | HYDRAULIC PUMP |
| XMSN | TRANSMISSION |



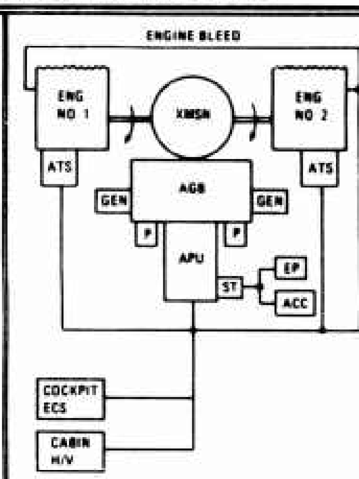

CONFIG A




CONFIG B




CONFIG C



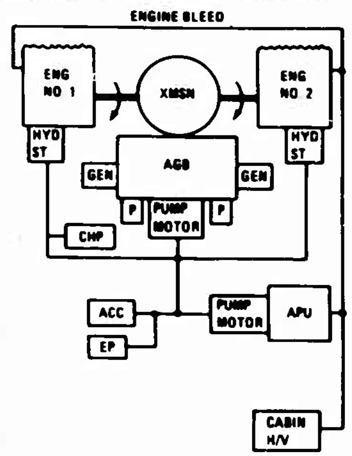

CONFIG D

| PARAMETER | WT FACTOR | CONFIG A 1970 | CONFIG A 1975 | CONFIG A 1985 | CONFIG A RATING 1970 | CONFIG A RATING 1975 | CONFIG A RATING 1985 | CONFIG B 1970 | CONFIG B 1975 | CONFIG B 1985 | CONFIG B RATING 1970 | CONFIG B RATING 1975 | CONFIG B RATING 1985 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| WEIGHT, COMPONENT & INSTL (LBS) | 13 | 515.7 | 427.6 | 384.6 | 12.5 | 12.7 | 12.8 | 512.6 | 430.0 | 371.9 | 12.6 | 12.6 | 12.6 |
| TOGW INFLUENCE (LB) (2.07) GROWTH FACTOR | 13 | 1116.8 | 916.2 | 755.8 | 11.9 | 12.2 | 12.8 | 1060.0 | 890.0 | 769.0 | 12.6 | 12.6 | 12.6 |
| 10-YR LIFE CYCLE COST PERCENT OF BASELINE | 10 | 128 | 137 | 170 | 8.1 | 8.6 | 8.1 | 123 | 135 | 166 | 8.7 | 8.8 | 8.3 |
| SPS RELIABILITY (FAILURES/1000 FLT HRS) | 10 | 29.4 | 21.3 | 16.1 | 7.1 | 7.5 | 8.0 | 27.3 | 70.9 | 15.2 | 8.0 | 8.2 | 8.7 |
| DISPATCH AVAILABILITY (FAILURES/1000 STARTS) | 10 | 11.1 | 8.1 | 6.0 | 6.8 | 8.3 | 9.8 | 11.1 | 8.1 | 6.0 | 6.8 | 8.3 | 9.8 |
| EFFECT ON AIRCRAFT COMPLEXITY | 8 | 2 | 2 | 2 | 7 | 7 | 7 | 1 | 1 | 1 | 8 | 8 | 8 |
| SPS COMPLEXITY | 8 | 4 | 4 | 4 | 5 | 5 | 5 | 2 | 2 | 2 | 7 | 7 | 7 |
| INTEGRATION COMPLEXITY | 8 | 1 | 1 | 1 | 8 | 8 | 8 | 2 | 2 | 2 | 7 | 7 | 7 |
| MAINTAINABILITY (MMH/1000 FLT HRS) | 4 | 107.7 | 82.0 | 61.2 | 3.2 | 3.4 | 3.5 | 104.8 | 80.1 | 60.0 | 3.35 | 3.5 | 3.6 |
| RANGE INFLUENCE (MILES) | 4 | 2.9 | 1.9 | 1.5 | 3.4 | 3.5 | 3.7 | 2.5 | 1.7 | 1.4 | 4 | 4 | 4 |
| PWR RQMTS (HP) | 4 | 76 | 74 | 71 | 3.4 | 3.4 | 3.4 | 66 | 64 | 62 | 4 | 4 | 4 |
| VOLUME | 4 | 5813 | 5548 | 4983 | 4.0 | 4.0 | 4.0 | 5818 | 5590 | 5002 | 4 | 4 | 4 |
| VULNERABILITY | 4 | 2 | 2 | 2 | 3.5 | 3.5 | 3.5 | 1 | 1 | 1 | 4 | 4 | 4 |
| TOTAL SCORE | | | | | 83.9 | 87.2 | 89.7 | | | | 90.0 | 92.0 | 94.2 |
| RANKING | | | | | 4 | 4 | 4 | | | | 3 | 2 | 2 |

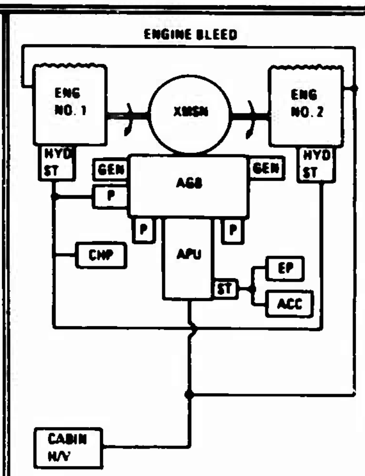
| PARAMETER | WT FACTOR | CONFIG C 1970 | CONFIG C 1975 | CONFIG C 1985 | CONFIG C RATING 1970 | CONFIG C RATING 1975 | CONFIG C RATING 1985 | CONFIG D 1970 | CONFIG D 1975 | CONFIG D 1985 | CONFIG D RATING 1970 | CONFIG D RATING 1975 | CONFIG D RATING 1985 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| WEIGHT, COMPONENT & INSTL (LBS) | 13 | 512.3 | 428.5 | 367.6 | 12.6 | 12.7 | [illegible]2.7 | 497 | 417.5 | 359.4 | 13 | 13 | 13 |
| TOGW INFLUENCE (LB) (2.07) GROWTH FACTOR | 13 | 1108.8 | 918.2 | 782.8 | 12.0 | 12.2 | 12.3 | 1029.0 | 865.0 | 744.0 | 13 | 13 | 13 |
| 10-YR LIFE CYCLE COST PERCENT OF BASELINE | 10 | 114 | 123 | 145 | 9.4 | 9.8 | 9.8 | 108 | 120 | 143 | 10 | 10 | 10 |
| SPS RELIABILITY (FAILURES/1000 FLT HRS) | 10 | 23.9 | 17.9 | 14.1 | 9.5 | 9.5 | 9.5 | 22.8 | 1. 0 | 13.5 | 10 | 10 | 10 |
| DISPATCH AVAILABILITY (FAILURES/1000 STARTS) | 10 | 8.4 | 6.9 | 5.9 | 10 | 10 | 10 | 8.4 | 6.9 | 5.9 | 10 | 10 | 10 |
| EFFECT ON AIRCRAFT COMPLEXITY | 8 | 2 | 2 | 2 | 7 | 7 | 7 | 1 | 1 | 1 | 8 | 8 | 8 |
| SPS COMPLEXITY | 8 | 3 | 3 | 3 | 6 | 6 | 6 | 1 | 1 | 1 | 8 | 8 | 8 |
| INTEGRATION COMPLEXITY | 8 | 1 | 1 | 1 | 8 | 8 | 8 | 2 | 2 | 2 | 7 | 7 | 7 |
| MAINTAINABILITY (MMH/1000 FLT HRS) | 4 | 96.9 | 76.4 | 59.0 | 3.7 | 3.7 | 3.7 | 90.1 | 71.1 | 54.9 | 4 | 4 | 4 |
| RANGE INFLUENCE (MILES) | 4 | 3.2 | 2.2 | 1.7 | 2.9 | 2.8 | 3.1 | 2.5 | 1.7 | 1.4 | 4 | 4 | 4 |
| PWR RQMTS (HP) | 4 | 86 | 82 | 78 | 2.8 | 2.9 | 3.0 | 66 | 64 | 62 | 4 | 4 | 4 |
| VOLUME | 4 | 7739 | 7455 | 6896 | 2.7 | 2.6 | 2.5 | 6741 | 6467 | 5907 | 3.4 | 3.3 | 3.3 |
| VULNERABILITY | 4 | 2 | 2 | 2 | 3.5 | 3.5 | 3.5 | 1 | 1 | 1 | 4.0 | 4.0 | 4.0 |
| TOTAL SCORE | | | | | 90.1 | 90.6 | 91.2 | | | | 98.4 | 98.3 | 98.3 |
| RANKING | | | | | 2 | 3 | 3 | | | | 1 | 1 | 1 |

## TABLE XLV. COMPARATIVE EVALUATION CHART FOR SPS WITHOUT COCKPIT COOLING AND WITH BACKUP ENGINE START

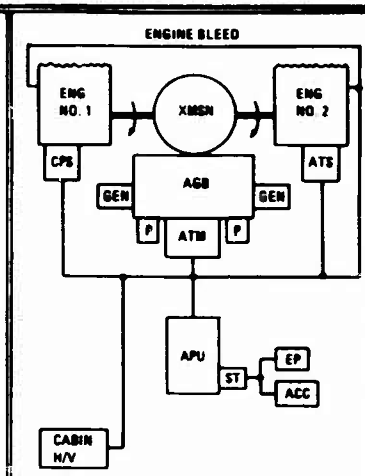
| Symbol | Meaning |
|---|---|
| ACC | HYD ACCUMULATOR |
| AGB | ACCESSORY GEARBOX |
| ATM | AIR TURBINE MOTOR |
| ATS | AIR TURBINE STARTER |
| CHP | CART – HYD PUMP |
| CPS | CART – PNEU STARTER |
| ECS | ENVIRONMENT CONTROL SYSTEM |
| ENG | ENGINE |
| EP | ELECTRIC MOTOR PUMP |
| GEN | AC GENERATOR |
| HYD ST | HYDRAULIC STARTER |
| P | HYDRAULIC PUMP |
| XMSN | TRANSMISSION |



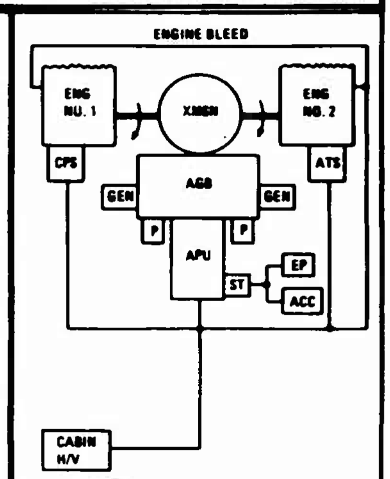

CONFIG A




CONFIG B




CONFIG C




CONFIG D

**CONFIG A**

| PARAMETER | WT FACTOR | 1970 | 1975 | 1985 | RATING 1970 | RATING 1975 | RATING 1985 |
|---|---|---|---|---|---|---|---|
| WEIGHT, COMPONENT & INSTL (LBS) | 13 | 531.4 | 437.2 | 370.9 | 11.9 | 12.2 | 12.3 |
| TOGW INFLUENCE (LB) (2.07) GROWTH FACTOR | 13 | 1147.8 | 936.2 | 788.8 | 11.3 | 11.7 | 11.9 |
| 10-YR LIFE CYCLE COST PERCENT OF BASELINE | 10 | 126 | 142 | 165 | 7.1 | 7.1 | 8.3 |
| SPS RELIABILITY (FAILURES/1000 FLT HRS) | 10 | 28.3 | 20.3 | 16.1 | 7.0 | 7.0 | 7.4 |
| DISPATCH AVAILABILITY (FAILURES/1000 STARTS) | 10 | 3.1 | 2.1 | 1.4 | 0 | 0 | 0 |
| EFFECT ON AIRCRAFT COMPLEXITY | 8 | 2 | 2 | 2 | 7 | 7 | 7 |
| SPS COMPLEXITY | 8 | 4 | 4 | 4 | 5 | 5 | 5 |
| INTEGRATION COMPLEXITY | 8 | 1 | 1 | 1 | 8.0 | 8.0 | 8.0 |
| MAINTAINABILITY (MMH/1000 FLT HRS) | 4 | 103.7 | 78.5 | 58.8 | 3.2 | 3.4 | 3.5 |
| RANGE INFLUENCE (MILES) | 4 | 2.9 | 1.9 | 1.5 | 3.4 | 3.5 | 3.7 |
| PWR RQMTS (HP) | 4 | 76 | 74 | 71 | 3.4 | 3.4 | 3.4 |
| VOLUME | 4 | 4080 | 3844 | 3377 | 4.0 | 4.0 | 4.0 |
| VULNERABILITY | 4 | 2 | 2 | 2 | 3.5 | 3.5 | 3.5 |
| TOTAL SCORE | | | | | 74.8 | 77.8 | 78.0 |
| RANKING | | | | | 4 | 4 | 4 |

**CONFIG B**

| PARAMETER | 1970 | 1975 | 1985 | RATING 1970 | RATING 1975 | RATING 1985 |
|---|---|---|---|---|---|---|
| WEIGHT, COMPONENT & INSTL (LBS) | 528.3 | 439.8 | 378.2 | 12.0 | 12.1 | 12.0 |
| TOGW INFLUENCE (LB) (2.07) GROWTH FACTOR | 1093 | 908 | 783 | 12.0 | 12.1 | 12.0 |
| 10-YR LIFE CYCLE COST PERCENT OF BASELINE | 120 | 132 | 166 | 8.5 | 8.8 | 8.6 |
| SPS RELIABILITY (FAILURES/1000 FLT HRS) | 25.9 | 19.2 | 14.2 | 8.1 | 8.3 | 8.9 |
| DISPATCH AVAILABILITY (FAILURES/1000 STARTS) | 3.1 | 2.1 | 1.4 | 0 | 0 | 0 |
| EFFECT ON AIRCRAFT COMPLEXITY | 1 | 1 | 1 | 8 | 8 | 8 |
| SPS COMPLEXITY | 2 | 2 | 2 | 7 | 7 | 7 |
| INTEGRATION COMPLEXITY | 2 | 2 | 2 | 7 | 7 | 7 |
| MAINTAINABILITY (MMH/1000 FLT HRS) | 100.8 | 76.6 | 57.8 | 3.4 | 3.5 | 3.8 |
| RANGE INFLUENCE (MILES) | 2.5 | 1.7 | 1.4 | 4.0 | 4.0 | 4.0 |
| PWR RQMTS (HP) | 66 | 64 | 62 | 4.0 | 4.0 | 4.0 |
| VOLUME | 4085 | 3886 | 3396 | 4.0 | 3.9 | 4.0 |
| VULNERABILITY | 1 | 1 | 1 | 4.0 | 4.0 | 4.0 |
| TOTAL SCORE | | | | 82.0 | 82.7 | 83.1 |
| RANKING | | | | 3 | 3 | 3 |

**CONFIG C**

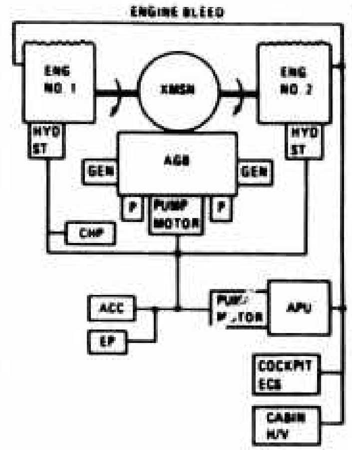
| PARAMETER | 1970 | 1975 | 1985 | RATING 1970 | RATING 1975 | RATING 1985 |
|---|---|---|---|---|---|---|
| WEIGHT, COMPONENT & INSTL (LBS) | 506.0 | 422.7 | 359.6 | 12.6 | 12.6 | 12.7 |
| TOGW INFLUENCE (LB) (2.07) GROWTH FACTOR | 1082.8 | 906.2 | 765.8 | 12.0 | 12.2 | 12.3 |
| 10-YR LIFE CYCLE COST PERCENT OF BASELINE | 111 | 124 | 144 | 9.4 | 9.5 | 9.8 |
| SPS RELIABILITY (FAILURES/1000 FLT HRS) | 22.9 | 17.2 | 13.4 | 9.5 | 9.5 | 9.5 |
| DISPATCH AVAILABILITY (FAILURES/1000 STARTS) | .78 | .64 | .55 | 10.0 | 10.0 | 10.0 |
| EFFECT ON AIRCRAFT COMPLEXITY | 2 | 2 | 2 | 7 | 7 | 7 |
| SPS COMPLEXITY | 3 | 3 | 3 | 6 | 6 | 6 |
| INTEGRATION COMPLEXITY | 1 | 1 | 1 | 8 | 8 | 8 |
| MAINTAINABILITY (MMH/1000 FLT HRS) | 92.9 | 72.9 | 56.6 | 3.7 | 3.7 | 3.7 |
| RANGE INFLUENCE (MILES) | 3.2 | 2.2 | 1.7 | 2.9 | 2.8 | 3.1 |
| PWR RQMTS (HP) | 86 | 82 | 78 | 2.8 | 2.9 | 3.0 |
| VOLUME | 6061 | 5827 | 5350 | 2.0 | 1.9 | 1.7 |
| VULNERABILITY | 2 | 2 | 2 | 3.5 | 3.5 | 3.5 |
| TOTAL SCORE | | | | 89.4 | 89.6 | 90.3 |
| RANKING | | | | 2 | 2 | 2 |

**CONFIG D**

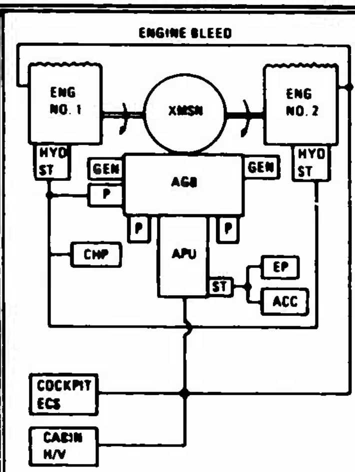
| PARAMETER | 1970 | 1975 | 1985 | RATING 1970 | RATING 1975 | RATING 1985 |
|---|---|---|---|---|---|---|
| WEIGHT, COMPONENT & INSTL (LBS) | 489.7 | 411.7 | 351.4 | 13 | 13 | 13 |
| TOGW INFLUENCE (LB) (2.07) GROWTH FACTOR | 1013 | 852 | 727 | 13 | 13 | 13 |
| 10-YR LIFE CYCLE COST PERCENT OF BASELINE | 104 | 118 | 136 | 10 | 10 | 10 |
| SPS RELIABILITY (FAILURES/1000 FLT HRS) | 21.81 | 16.4 | 12.8 | 10 | 10 | 10 |
| DISPATCH AVAILABILITY (FAILURES/1000 STARTS) | .78 | .64 | .55 | 10 | 10 | 10 |
| EFFECT ON AIRCRAFT COMPLEXITY | 1 | 1 | 1 | 8 | 8 | 8 |
| SPS COMPLEXITY | 1 | 1 | 1 | 8 | 8 | 8 |
| INTEGRATION COMPLEXITY | 2 | 2 | 2 | 7 | 7 | 7 |
| MAINTAINABILITY (MMH/1000 FLT HRS) | 86.1 | 67.6 | 52.6 | 4 | 4 | 4 |
| RANGE INFLUENCE (MILES) | 2.5 | 1.7 | 1.4 | 4 | 4 | 4 |
| PWR RQMTS (HP) | 66 | 64 | 62 | 4 | 4 | 4 |
| VOLUME | 5063 | 4839 | 4361 | 3.0 | 3.0 | 2.8 |
| VULNERABILITY | 1 | 1 | 1 | 4.0 | 4.0 | 4.0 |
| TOTAL SCORE | | | | 98.0 | 98.0 | 97.8 |
| RANKING | | | | 1 | 1 | 1 |

# TABLE XLVI. COMPARATIVE EVALUATION CHART FOR SPS WITH COCKPIT COOLING & WITH BACKUP START

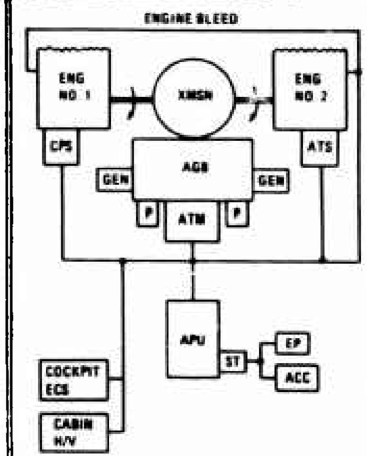
- ACC — HYD ACCUMULATOR
- AGB — ACCESSORY GEARBOX
- ATM — AIR TURBINE MOTOR
- ATS — AIR TURBINE STARTER
- CHP — CART - HYD PUMP
- CPS — CART - PNEU STARTER
- ECS — ENVIRONMENT CONTROL SYSTEM
- ENG — ENGINE
- EP — ELECTRIC MOTOR PUMP
- GEN — AC GENERATOR
- HYD ST — HYDRAULIC STARTER
- P — HYDRAULIC PUMP
- XMSN — TRANSMISSION



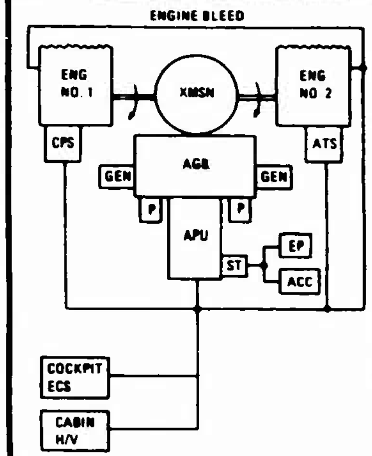

CONFIG A




CONFIG B




CONFIG C




CONFIG D

| PARAMETER | WT FACTOR | CONFIG A 1970 | CONFIG A 1975 | CONFIG A 1985 | CONFIG A RATING 1970 | CONFIG A RATING 1975 | CONFIG A RATING 1985 | CONFIG B 1970 | CONFIG B 1975 | CONFIG B 1985 | CONFIG B RATING 1970 | CONFIG B RATING 1975 | CONFIG B RATING 1985 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| WEIGHT, COMPONENT & INSTL (LBS) | 13 | 563.0 | 467.2 | 399.8 | 12.0 | 12.2 | 12.3 | 559.9 | 489.6 | 407.1 | 12.1 | 12.2 | 12.1 |
| TOGW INFLUENCE (LB) (2.07) GROWTH FACTOR | 13 | 1213.8 | 898.2 | 848.8 | 11.7 | 11.8 | 12.0 | 1159.0 | 971.0 | 843.0 | 12.0 | 12.2 | 12.1 |
| 10-YR LIFE CYCLE COST PERCENT OF BASELINE | 10 | 135 | 145 | 175 | 8.0 | 8.3 | 8.5 | 129 | 142 | 173 | 8.6 | 8.8 | 8.6 |
| SPS RELIABILITY (FAILURES/1000 FLT HRS) | 10 | 29.4 | 21.3 | 16.1 | 7.4 | 7.8 | 8.8 | 27.3 | 20.2 | 15.2 | 8.2 | 8.4 | 9.0 |
| DISPATCH AVAILABILITY (FAILURES/1000 STARTS) | 10 | 3.1 | 2.1 | 1.4 | 0 | 0 | 0 | 3.1 | 2.1 | 1.4 | 0 | 0 | 0 |
| EFFECT ON AIRCRAFT COMPLEXITY | 8 | 2 | 2 | 2 | 7 | 7 | 7 | 1 | 1 | 1 | 8 | 8 | 8 |
| SPS COMPLEXITY | 8 | 4 | 4 | 4 | 5 | 5 | 5 | 2 | 2 | 2 | 7 | 7 | 7 |
| INTEGRATION COMPLEXITY | 8 | 1 | 1 | 1 | 8 | 8 | 8 | 2 | 2 | 2 | 7 | 7 | 7 |
| MAINTAINABILITY (MMH/1000 FLT HRS) | 4 | 108.7 | 83.0 | 62.2 | 3.2 | 3.4 | 3.5 | 105.8 | 81.1 | 61.0 | 3.4 | 3.5 | 3.6 |
| RANGE INFLUENCE (MILES) | 4 | 2.9 | 1.9 | 1.5 | 2.9 | 2.8 | 3.1 | 2.5 | 1.7 | 1.4 | 4 | 4 | 4 |
| PWR RQMTS (HP) | 4 | 76 | 74 | 71 | 3.4 | 3.1 | 3.1 | 66 | 64 | 62 | 4 | 4 | 4 |
| VOLUME | 4 | 5955 | 5689 | 5082 | 4.0 | 4.0 | 3.3 | 5980 | 5711 | 5111 | 3.9 | 3.9 | 3.9 |
| VULNERABILITY | 4 | 2 | 2 | 2 | 3.5 | 3.5 | 3.5 | 1 | 1 | 1 | 4 | 4 | 4 |
| TOTAL SCORE | | | | | 78.1 | 78.9 | 79.0 | | | | 82.1 | 82.8 | 83.3 |
| RANKING | | | | | 4 | 4 | 4 | | | | 3 | 3 | 3 |

| PARAMETER | WT FACTOR | CONFIG C 1970 | CONFIG C 1975 | CONFIG C 1985 | CONFIG C RATING 1970 | CONFIG C RATING 1975 | CONFIG C RATING 1985 | CONFIG D 1970 | CONFIG D 1975 | CONFIG D 1985 | CONFIG D RATING 1970 | CONFIG D RATING 1975 | CONFIG D RATING 1985 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| WEIGHT, COMPONENT & INSTL (LBS) | 13 | 538.6 | 456.7 | 388.5 | 12.8 | 12.5 | 12.7 | 521.3 | 441.7 | 380.3 | 13 | 13 | 13 |
| TOGW INFLUENCE (LB) (2.07) GROWTH FACTOR | 13 | 1158.8 | 976.2 | 825.8 | 12.0 | 12.1 | 12.4 | 1080.0 | 915.0 | 787.0 | 13 | 13 | 13 |
| 10-YR LIFE CYCLE COST PERCENT OF BASELINE | 10 | 119 | 134 | 154 | 9.2 | 9.2 | 9.8 | 113 | 126 | 152 | 10 | 10 | 10 |
| SPS RELIABILITY (FAILURES/1000 FLT HRS) | 10 | 24.4 | 18.3 | 14.4 | 9.5 | 9.5 | 9.6 | 23.2 | 17.4 | 13.8 | 10 | 10 | 10 |
| DISPATCH AVAILABILITY (FAILURES/1000 STARTS) | 10 | .78 | .64 | .55 | 10 | 10 | 10 | .78 | .64 | .55 | 10 | 10 | 10 |
| EFFECT ON AIRCRAFT COMPLEXITY | 8 | 2 | 2 | 2 | 7 | 7 | 7 | 1 | 1 | 1 | 8 | 8 | 8 |
| SPS COMPLEXITY | 8 | 3 | 3 | 3 | 6 | 6 | 6 | 1 | 1 | 1 | 8 | 8 | 8 |
| INTEGRATION COMPLEXITY | 8 | 1 | 1 | 1 | 8 | 8 | 8 | 2 | 2 | 2 | 7 | 7 | 7 |
| MAINTAINABILITY (MMH/1000 FLT HRS) | 4 | 97.9 | 77.4 | 60.0 | 3.7 | 3.7 | 3.7 | 91.1 | 72.1 | 55.9 | 4 | 4 | 4 |
| RANGE INFLUENCE (MILES) | 4 | 3.2 | 2.2 | 1.7 | 2.9 | 2.8 | 3.1 | 2.5 | 1.7 | 1.4 | 4 | 4 | 4 |
| PWR RQMTS (HP) | 4 | 86 | 82 | 78 | 2.8 | 2.8 | 3.0 | 66 | 64 | 62 | 4 | 4 | 4 |
| VOLUME | 4 | 7936 | 7652 | 7065 | 2.7 | 2.6 | 2.5 | 6938 | 6864 | 6076 | 3.4 | 3.4 | 3.4 |
| VULNERABILITY | 4 | 2 | 2 | 2 | 3.5 | 3.5 | 3.5 | 1 | 1 | 1 | 4 | 4 | 4 |
| TOTAL SCORE | | | | | 89.9 | 89.7 | 91.3 | | | | 98.4 | 98.4 | 98.4 |
| RANKING | | | | | 2 | 2 | 2 | | | | 1 | 1 | 1 |

## TOGW Influence

This parameter indicates the growth in aircraft gross weight due to the addition of SPS equipment weight. A growth factor of 2.07 was used for all SPS equipment. This factor is defined here as the multiple of equipment weight that relates the weight of the added equipment to the resulting increase in overall gross weight of the aircraft. This increase in aircraft gross weight includes the weights of added equipment and installation hardware, added airframe structure, and added fuel and fuel tank capacity. With remote APU configurations, additional weight increments of 48.8, 31.2, and 21.8 pounds were added for the successive technology levels. Installations with direct-coupled APU's have less impact on aircraft weight than those with remote APU's.

## Life-Cycle Cost

The life-cycle cost analysis previously discussed generated the ten-year system cost for each SPS configuration, including all recurring and nonrecurring costs. Because the existing technology configuration D baseline system had the lowest life-cycle cost, the costs of the other configurations were all expressed in relation to this. In particular, backup engine starting would increase cost by 4 percent and cockpit ECS by 8 percent.

## Reliability

SPS reliability was expressed in terms of total system failure rate. Configuration D was the optimum configuration in this regard, although it was not much better than configuration C.

## Dispatch Availability

Dispatch availability is a measure of the probability of <u>not</u> accomplishing main-engine starting due to failures of SPS components. Without backup main-engine starting (starting with an inoperable APU) this factor is based on failure rates of the APU and its starting system, the engine starter, and the plumbing, modified by a factor which accounts for the proportion of these failures that prevent main-engine starting. With backup starting, the probability of obtaining the desired backup starting when required is factored into the dispatch availability.

Pneumatic main-engine starting provides more reliable dispatch capability than hydraulic starting, and, as expected, the improvement with backup starting capability is dramatic.

### Complexity

Three categories of complexity were considered - effect on aircraft complexity, secondary power system complexity, and system integration complexity - and all three categories were given ratings based on engineering judgment.

### Maintainability

Maintainability was expressed in terms of MMH per thousand flight hours. Configuration D was superior in terms of maintainability.

### Range Influence

The range influence factor accounts for aircraft range reduction corresponding to the fuel consumed by the APU during a 10-minute preflight check.

### Power Requirements

The values listed for this parameter are the sizes of the APU's, expressed in terms of ESHP.

### Volume

The volumes are those of SPS components and interconnecting piping and tubing.

### Vulnerability

Vulnerability was evaluated on the basis of volume, and on the basis of shielding as determined by component location.

## TRADE-OFF STUDY CONCLUSIONS

### Selected System

The system selected, as a result of trade-off studies, is configuration D. It consists of a bleed-air APU (shown in Figure 3) which is mounted on and drives directly into the AGB. Also included are an air-cycle machine, an air turbine starter (mounted on each engine), and the necessary pneumatic plumbing. The APU is started from a hydraulic accumulator and provides bleed airflow for engine starting, simultaneously with electric and hydraulic power generation to provide the ancillary services required during the engine start cycle. Operation of the APU and the SPS accessories is independent of main engine and/or rotor operation for ground checkout.

The principal parameters which forced the configuration selection are:

| Function | Method Selected | Principal Reason |
|---|---|---|
| Main Engine Starting | Air Turbine Starter | Dispatch Reliability of Pneumatic Starting |
| APU Starting | Hydraulic | All-Weather Capability With Unlimited Multi-Start Capability |
| Hydraulic & Electric Power Drive Both Flight and Ground | AGB | Simplest for Both Main Transmission and APU Drive |
| APU Cycle/ Configuration | Single Shaft Combination Bleed/Shaft | Least Cost, Most Reliable, Only Slight Start Weight Penalty due to Driving AGB During Start |
| ECS | Air Cycle | Reliability and Weight |
| Backup Starting | Cartridge/Pneumatic Turbine Starter | Lightest, Simplest to Incorporate, Least Cost |

SPS Configuration

Configuration D, a pneumatic system with a direct APU driven AGB, is clearly the optimum selection for the requirements established and the ground rules of the study. The principal reasons for this are its low life-cycle cost and its improved system and dispatch reliabilities. This conclusion would be drawn regardless of the weighting factor because for the majority of cases of the evaluation parameters, it was the best.

A primary consideration relating to validity of the trade-off results is cost-effectiveness. The effectiveness of each of the configurations is the same, since each performed the same function or mission. Thus, effectiveness can be considered as a common denominator or baseline for the synthesis of SPS configurations and determination of SPS performance. All parameters were determined on this basis. For example, the APU in all cases was sized to provide the required shaft and bleed power required for SPS ground and flight operation. Thus, with a common effectiveness for all SPS candidate configurations, the cost/effectiveness parameter is directly measured by life cycle-cost. The SPS life-cycle cost includes all recurring and nonrecurring costs such as RDTE, initial investment, operation and maintenance, and overhead. The operation and maintenance costs take into account reliability and all levels of maintenance. The life-cycle cost results obtained therefore substantiate the conclusion that configuration D is the optimum selection.

Based on the results of this evaluation study and its validity considerations, it is recommended that configuration D (pneumatic starting and single-shaft APU with direct AGB drive) be considered for the proposed application. Development programs where necessary to achieve this goal in a timely manner should be initiated and pursued.

## REQUIRED RESEARCH AND DEVELOPMENT

The SPS component survey, APU parametric study, and succeeding trade-off studies and evaluations uncovered technological shortcomings which influenced component capability and impacted unfavorably on the total system performance, weight, and cost. Task V, then, identified those areas where technological advancements could provide significant improvements for future aircraft, particularly the following SPS components: compressors, turbines, combustors, seals, gears, shafting, bearings, hydraulic pumps, heat exchangers, and pneumatic and electrical systems. Optimum component redundancy, environmental protection, optimum power generation and distribution, and emergency power requirements were also considered. This section documents the available technology in these areas and the recommended research and development to accomplish the desired technological advancements, including time and cost estimates.

Advances in component technologies will contribute to significant improvements in the SPS characteristics - performance; weight and/or volume and mechanical integrity - within the constraints of reasonable production cost. However, it is possible that technological advancements which result in improvements in one of these areas may impact unfavorably on either or both of the others. Conversely, an advancement which brings improvement in one area may be accompanied by improvements in either or both of the others, also. It is important, then, to formulate the recommended research and development program to achieve the desired balance of system characteristics.

An element of risk is involved in the research and development programs to accomplish each technological advancement, and for this reason, alternative routes or technical approaches occasionally were suggested to achieve the desired objective.

### AUXILIARY POWER UNIT

No APU engines presently in production or being developed have the combined bleed air and shaft horsepower capability to match the specific SPS requirements. Any "off-the-shelf" APU would compromise system performance, weight, or volume. For these reasons, the development of an engine tailored to the SPS application is one of the recommended R&D programs.

Concurrent programs to advance the technologies of the APU components are also suggested, including research and development efforts pertaining to the centrifugal compressor, radial turbine, combustor, gears, bearings, shafts, and seals.

## Auxiliary Power Unit

### Background and Aims:

The survey of APU manufacturers in Task I revealed that there was no engine in production or development status (no "off-the-shelf" engine) sized to provide bleed air and shaft power matching the SPS requirements and utilizing the full thermodynamic capability of the engine.

To supply the SPS power and pneumatic requirements by operating a production APU configuration at part power would compromise the engine performance and would result in a heavier and larger volume machine than one specifically designed for the SPS application. Considering the relationships between engine performance parameters and the thermodynamic design parameters of compressor pressure ratio and turbine-inlet temperature, specific power (horsepower per pound of compressor airflow) varies directly with turbine-inlet temperature and, to a lesser extent, with pressure ratio. At turbine temperature, and pressure ratios lower than the design values - corresponding to part-power engine operation - specific power would be less than at the design point. Consequently, to match the SPS requirements, the engine airflow would have to be larger and the engine larger and heavier than an APU designed specifically for this application, with the thermodynamic capability established in the study.

Furthermore, specific fuel consumption varies directly with compressor pressure ratio and is secondarily dependent on turbine temperature. The lower pressure ratio at part-power conditions for an existing APU would result in poorer SFC than would be the case for an engine designed for this application. Also, in addition to this direct impact on performance, lower pressure ratio of the bleed air means larger pneumatic duct size as well as larger air turbine starters for the main engines. So the lower pressure ratio would compromise both performance and SPS weight.

Optimum engine performance and minimum weight could be achieved by designing and developing an APU specifically for the secondary power system, utilizing thermodynamic capability

consistent with the compressor pressure ratio and turbine-inlet temperature technologies established in the study. Component efficiencies and losses compatible with the state-of the art would further enhance the engine design configuration and impact favorably on system characteristics. Materials selection and bearing and gear design should also be representative of the latest available technology.

Objective:

The objective of this program is to design and develop an APU sized to provide bleed air and shaft power matching the SPS requirements. Engine performance and weight would be optimized for the proposed production time frame by utilizing thermodynamic capability compatible with advanced technology compressor pressure ratio and turbine-inlet temperature and state of the art component performance.

Technical Approach:

1. Establish compressor, combustor, and turbine efficiencies and losses consistent with state of the art component performance, utilizing applicable data from contemporary development programs and developing new components with the desired technologies.

2. Define design concepts and configurations for gears, bearings, shafts, and seals which are compatible with advanced design practices.

3. Select materials, particularly for combustor and turbine applications, which reflect the state of the art in high-temperature technologies.

4. Incorporate these advances in an APU tailored to the SPS requirements and develop and test the engine, to achieve qualification in the desired time frame for aircraft production.

## Centrifugal Compressor

### Background and Aims:

The results of Task II parametric APU study illustrated the impact of component efficiency improvements, among them compressor efficiency improvements, on engine performance. In the very small centrifugal machines considered in this study, machining tolerances, surface finishes, and clearances strongly influence aerodynamic performance and efficiency. In scaling compressors to smaller size, it becomes increasingly difficult to scale tolerances, finishes, and clearances proportionally, and the result is much lower efficiencies in small turbomachinery.

Achieving close tolerances becomes a function of the method of fabrication, tooling, and manufacturing procedure. Some aerodynamic shapes are readily adaptable to production methods which yield close tolerances, and these must be evaluated to define their performance and to provide the basis for trade-off studies.

Clearances between the rotating impeller and stationary housing are necessary because of impeller growth caused by rotational forces and because of differential thermal growth. Furthermore, transient temperature conditions often determine minimum clearances and compromise performance for steady-state operating points. Clearances should be minimized by appropriate use of cooling and proper selection of materials. Abradable material strips at the impeller shroud lines, which permit the rotating blades to establish the smallest clearances required, should be investigated. Composite reinforced plastic materials used as liners for the compressor wheel shrouds offer another alternative to obtain smaller allowable wheel clearances.

Other centrifugal compressor research programs will achieve improved efficiencies through better aerodynamic design procedures, and it is anticipated that these improvements also will pertain to the SPS program, without the requirements for additional funding. The Task II parametric APU performance results showed the benefit of higher pressure ratios in improvements in SFC. It is anticipated, also, that research programs devoted to higher pressure ratios in single-stage centrifugal impellers will require no additional funding. One consequence of higher pressure ratios is that design concepts

must be developed which provide bleed air at relatively low pressures, rather than at the compressor exit pressure.

Another performance aspect of the centrifugal machine to be explored is the desired wide airflow range, occasioned by the varying demands for bleed air but the requirement for relatively constant quality (pressure and temperature). Variable inlet guide vanes in conjunction with a variable-area diffuser offer the opportunity to extend this operating range, but the knowledge about their use must be increased. Materials must be developed to be used in these variable aerodynamic components, which minimize leakage and do not require lubrication. Desirable properties for these materials include minimum breakaway and running friction, resistance to oxidation and wear, and minimum susceptibility to galling. Variable geometry also provides another possible application of abradable materials to minimize leakage and losses.

Objectives:

The objectives of the centrifugal compressor technology advancement program are increased efficiency, pressure ratio, and flow range for compressors in the 1.0 to 2.0 lb air/sec class.

Technical Approach:

1. Define compressor aerodynamic designs to achieve high performance which are compatible with the capabilities and limitations of impeller fabrication equipment, and which fully exploit the accuracy capability of this equipment. Determine design concept which results in minimum clearances between the rotating impeller and the stationary shroud.

2. Establish pressure ratio capability of the single-stage centrifugal compressor within the constraints of anticipated improvements in efficiency. Determine optimum bleed configurations to provide compressor bleed air at pressures lower than the exit pressure.

3. Define aerodynamic design characteristics tending to provide wide airflow range capability. Design and evaluate variable inlet guide vanes and variable diffuser vanes as a means of extending this operating range.

## Radial Turbine

### Background and Aims:

The radial-inflow turbine efficiency is equally as important as the centrifugal compressor efficiency with regard to its impact on APU engine performance. The turbine efficiency is influenced strongly by tolerances, surface finishes, and clearances, too. So, those radial turbine designs which are adaptable to production methods which yield close tolerance must be evaluated to define their performance potential, to quantify the interrelationships between tolerances and performance, and to provide the basis for trade-off studies. Also, clearances should be minimized by appropriate use of cooling and proper selection of materials, and the use of abradable materials at the impeller shroud lines should be investigated.

It is anticipated that other research programs will be devoted to improved turbine aerodynamic performance as well as higher stage loading (in line with the increased compressor pressure ratio), and the results will pertain to the SPS program, without requiring additional funding.

High turbine-inlet temperatures are desirable to achieve high specific power (horsepower per pound of engine airflow), and they also contribute to improvement in SFC. However, higher turbine temperatures will place more stringent requirements on turbine blade and disc materials and/or require cooling of blades and discs. For existing technology turbomachinery, 1800°F is a reasonable turbine-inlet temperature and can be achieved without blade cooling. Improvements in the thermal capability of high-temperature materials can be expected to follow a general trend of 20°F to 30°F per year increase in turbine-inlet temperature. Beyond that, cooling of blades and discs must be employed to reach the higher anticipated turbine temperatures.

Erosion-resistant ceramic or intermetallic composite materials offer one possible alternative for high-temperature materials. Beryllides are one such compound material with this potential. Columbium base alloys with diffused metallic coatings for protection against oxidation and sulfidation offer another alternative route to high turbine-inlet temperature protection. An additional alternative is provided by the higher strength capabilities of nickel-base cast or forged alloys. To achieve

turbine-inlet temperatures higher than those provided by the improvements in material capabilities, internal cooling provisions must be designed and evaluated, and fabrication techniques must be defined.

The airflow through the APU engine is controlled by the turbine nozzle area, being proportional to the product of area and turbine-inlet pressure and inversely proportional to the square root of turbine temperature. For part-power operation, particularly when variable compressor geometry is utilized to produce bleed air of constant quality (pressure and temperature), variable turbine nozzles are required to maintain good performance. Furthermore, variable turbine nozzles provide quick response to increased power demand when operating at part-power conditions. The variable nozzles permit a rapid increase in flow, rather than turbine temperature, for rapid transient acceleration without surge.

Developing the variable nozzle design without excessive leakage losses suggests another potential application for abradable materials. Materials which offer the possibility of nonlubricated bearings for variable-geometry concepts must be developed too. These materials should provide low breakaway and running friction, minimum susceptibility to galling, and resistance to oxidation and wear.

Objectives:

The objectives of the radial turbine technology advancement program are improved efficiency and increased stage loadings for radial turbines, higher inlet-temperature capability, and evaluation of variable stators for part-power and transient operation.

Technical Approach:

1. Define high-performance radial turbine aerodynamic designs which are compatible with the capabilities and limitations of fabrication equipment, and which fully exploit the accuracy capability of this equipment. Determine design concepts which result in minimum clearances between the rotating turbine wheel and the stationary shroud.

2. Establish turbine stage loading capability consistent with anticipated efficiency improvements.

3. Select and evaluate materials for high-temperature turbine operation, including:

    a. Ceramic and intermetallic composite materials

    b. Columbium alloys with diffused metallic coatings

    c. High-strength nickel-base cast and forged alloys

4. Evaluate internal cooling concepts for cast and fabricated impeller configurations.

5. Design and evaluate variable turbine nozzles for part-load and transient APU operation, investigating materials which require no lubrication for bearing applications and abradable materials to minimize leakage losses.

## Combustor

### Background and Aims:

Efficiency, pressure loss, turbine-inlet temperature pattern factor, ignition limits, and flammability limits are the combustor performance parameters that relate directly to APU engine performance. Combustor shape, volume, and carbon-forming tendencies are also of considerable importance to the APU configuration. Since the combustor efficiency is generally greater than 98 percent, this parameter will not be a matter of concern in the SPS advanced development program.

Combustor pressure loss is generally in the range of 2.5 to 5.0 percent of inlet total pressure. Pressure loss is a function of combustor liner geometry, so changes in geometry may impact strongly on this performance parameter. Turbine-inlet temperature pattern factor becomes increasingly important in the advanced technology APU engines with their higher temperature, and both radial and circumferential patterns must be carefully considered. Because of the small sizes of turbomachinery envisioned in the SPS study, cooling the radial turbine impeller and blades poses a severe problem - due to the minute cooling passages and the resulting laminar heat transfer characteristics. Careful control of the radial temperature gradients must be included in combination with cooling concepts to achieve the desired high temperatures. These factors are the basic criteria which will be used to assess changes in combustor design leading toward reduced volume and variations in shape tailored to the desired envelope of the APU.

Moreover, the range of operating conditions (altitude, ambient temperature, part-power operation, variations in bleed requirements) must be evaluated with regard to their impact on the combustor operation.

Uniform distribution of the combustor inlet air is necessary to the extent that maldistribution of the flame pattern is minimized and controlled radial temperature gradients at the turbine inlet can be achieved. This will permit operation at the desired high turbine temperatures while at the same time reducing requirements for cooling-air or material advancements.

Improvements in primary (combustion) zone mixing must be realized to provide uniform flame distribution and more

uniform gas temperatures at the turbine inlet. This would entail better methods of fuel injection and better methods of mixing combustion air with fuel. Moreover, improvements must be achieved in mixing of secondary (dilution) air to produce the desired turbine inlet temperature pattern factor and to shape the desired profile. Improvements in primary zone mixing would result in reduced combustor volume, and a favorable impact on engine volume and weight, while better secondary mixing would shorten the combustor and also contribute to reduced volume.

Efficient means of wall cooling must be devised to minimize the dilution air required and its associated pressure losses. Liner temperatures will become increasingly more critical as higher combustion temperatures are achieved. Consequently, new materials must be developed to withstand the severe oxidation and sulfidation conditions at high temperatures, concurrently with improvements in cooling.

Emulsified or gelled fuels possibly will become a requirement for the aircraft main engines, to alleviate the fire hazard associated with liquid fuels. The impact of emulsified fuels on the APU engine must be assessed.

Objectives:

The objectives of the combustor technology advancement program are improvements in the internal flow distributions (inlet air distribution, primary mixing, dilution air mixing, and wall cooling flows) to achieve minimum pressure losses and temperature pattern factors consistent with the desired high temperatures. In conjunction with these performance objectives, the internal improvements should result in reduced combustor length, volume, and weight in a shape tailored to the APU envelope.

Technical Approach:

1. Correlate combustor inlet flow maldistribution with its effect on temperature pattern factor and flame pattern to define limits for flow variations. Define and evaluate design concepts to minimize the effects of poor flow distribution.

2. Determine satisfactory concepts for fuel injection to improve flame distribution, and combustion-air mixing concepts to increase airflow residence time.

3. Determine the empirical correlations for optimum size, shape, and spacing of mixing jets required to achieve the desired turbine inlet temperature profile.

4. Define the film cooling air amounts and cooling air injection configurations to minimize the quantity of air required for liner cooling.

5. Determine the composition of alloys resistant to oxidation and sulfidation at high temperatures, applicable to liners.

6. Define the requirements for APU combustors using emulsified fuels.

## Seals

### Background and Aims:

The seal technology advancement program will be concerned with contact type shaft seals for retention of lubrication oil as well as labyrinth seals to minimize leakage of compressor air.

Satisfactory methods to retain lubrication oil inside the gearbox are a necessity (primarily, leakage can affect performance of gears and bearings after a period of time, while producing a fire hazard and resulting in an objectionable appearance). Moreover, leakage rates are difficult to establish in field operation, nor is there an acceptable criterion to rate a potential seal failure, so it is impossible to judge gearbox capability with reference to length of time it can operate safely. For the high rotational speeds associated with advancements in APU technology, the deficiencies in seal technology become more critical. Seal selection and the desired effectiveness must be achieved by considering the following interdependent operational, dimensional, and environmental factors:

- Rubbing velocity
- Pressure
- Temperature
- Shaft Surface Finish
- Material

Leakage of high-pressure compressor discharge air bypassing the turbine nozzle has a substantial impact on engine performance. Labyrinth seals should be prescribed for this leakage problem, and suitable design concepts must be determined.

### Objective:

The objective of the seal technology program is to improve the effectiveness and reliability of seals for retention of lubrication oil and for reduction of high-pressure air leakage.

### Technical Approach:

1. Review the present state of knowledge concerning each design element of contact-type shaft seals, in order to identify design criteria and recommend practices for each

element. Define each criterion in terms of conditions, requirements, limitation, or standards to be met in order to achieve successful and reliable design. Establish recommended practices based on solutions of design problems.

2. Evaluate labyrinth seal configurations to reduce leakage flow of compressor air, in order to define suitable design concepts for the APU.

## Gears

### Background and Aims:

The unit load approach can be used to rate the load capacity of a particular gear design. This method has distinct advantages in that all the variables are given in simple terms and are readily measurable quantities. Unit load is defined as an equivalent load in pounds per inch of face on a tooth of dimetral pitch, having a 1-inch face width. Increase in load capacity will evolve from new gear materials, advanced gear tooth forms, improved tooth surface finish, development of precision forged gear teeth with improved grain flow, increased gear housing stiffness (thus reducing case deflections), improved profile tolerances, new lubricants with increased load capacity, and improved methods of manufacturing, processing, and heat treatment.

Advanced gear materials offer the potential of operating at substantially increased surface loading, without scuffing of the tooth surface.

Increased load capacity also can be achieved through the development of new tooth forms which provide more area in contact, reduced surface stress, and reduced sliding velocity. Such tooth design not only improves the load-carrying capacity, but also improves oil film formation, reduces surface friction and heat, and reduces cooling requirements for the transmission. A potential increase of at least 50 percent in allowable tooth loading seems attainable.

Further improvements in load-carrying capacity and operational life can be achieved by improvements in tooth finishes. Honed gears, with a surface finish of 8 rms compared to the conventional 23 rms for ground gears, should be able to attain a 50- to 65-percent increase in permissible surface stress. Further developments could improve the surface finish to 3 or 4 rms, with a corresponding increase in allowable surface stress. The goal would be to produce these surfaces without adversely affecting the cost effectiveness of the gear system.

In the relatively small gear sizes required for the APU, these improvements in load capacity and unit load must be considered in the context of the associated reductions in gear face width. It can be envisioned that changes in face width would be sufficient to reach the point where structural rigidity would

become a problem. At that point, the improvements in load capacity would be reflected in increased mechanical integrity.

The gear housing is one potential application for composite reinforced plastics which could achieve the required stiffness (for reduced case deflections) with a substantial weight saving.

Objectives:

The objectives of the gear technology advancement program are to decrease the dimensions (and weight) and to increase the mechanical integrity of gears by increasing load capacity, to reduce gearbox cooling requirements, and at the same time to increase gear life.

Technical Approach:

1. Define and evaluate advanced gear materials for increased surface loading and reduced scuffing wear.

2. Determine potential new tooth forms to increase load capacity; select and develop promising concepts.

3. Establish possible improvements in tooth tolerance and surface finishes as a function of advanced fabrication techniques.

4. Evaluate application of composite reinforced plastics in gear housings.

## Shafting

### Background and Aims:

Highly-loaded, high-speed shafting is a potential application for beryllium, which offers the possibility of substantial weight savings compared to steel. Because of its low ductility (brittleness) and fatigue characteristics, beryllium is not suitable for impeller blades or stationary vanes in the air or gas flowpath. It will shatter when struck by another object, as might occur in the case of foreign-object ingestion. However, beryllium is a promising material for shaft applications, which avoid problems which might arise due to its brittleness but exploit its potential weight savings.

### Objectives:

The objectives of this technology advancement program are to evaluate beryllium as a material for shafting and to evaluate fabrication techniques for beryllium.

### Technical Objectives:

1. Evaluate the properties of beryllium forgings obtained from billets, ingots, and powder metallurgy and perform vibration and shock testing of test samples.

2. Investigate methods of machining beryllium and inspection techniques for evaluating raw material, in-process fabrication, and finished machining.

## Bearings

### Background and Aims:

The high rotational speeds anticipated for the APU lead to severe design requirements for the bearings. (The common measure of bearing speed capability is its DN value, where D is the bore diameter in millimeters and N is the rpm of the shaft). Technology development will be required for these high-speed bearings, to result in shaft dynamics compatible with the desired turbomachinery clearances and to minimize bearing losses. Development of rolling-contact bearings will be the prime bearing technology advancement task, while oil-lubricated journal bearings and gas-lubricated journal bearings will be considered as alternative concepts.

The primary aim of this program will be to operate relatively small rolling-contact bearings at DN values greater than $1.8 \times 10^6$ mm-rpm, while maintaining high reliability and long life. As a result of the high speeds, bearing design characteristics and parameters become critical, including cooling, lubrication, hydrodynamic power losses, outer ring stresses and fatigue life, skidding of rolling elements, and the bearing spin/roll ratio.

At present there appears to be no vast potential for bearing life improvement from the incorporation of new materials; however, it appears that large gains in bearing life will be made by the modification of basic bearing geometry, new manufacturing and processing techniques, new heat-treatment procedures, improved finishes and tolerances, and new lubricants and lubricating techniques. After these developments have contributed greatly to the increase of rolling-element bearing life, the time will have come for further advancements with new materials, which generally take a longer time to develop than design and manufacturing techniques.

To provide safety to the bearings in case of loss of oil, each bearing installation can be designed with special features to permit operation without oil. One of these design features incorporates a new bearing cage consisting of a metal or composite shroud with pocket inserts of a solid, compact lubricant (a composition of tantalum and molydisulfide). While operating normally with oil, the pocket insert material (solid lubricant) is transferred by the rollers or balls to the inner and outer bearing races, reducing friction and

lowering the operating temperature. However, the ability to operate without oil is its greatest attribute.

The operating life of rolling-element bearings may become unacceptable due to the high speed requirements. One possible alternative would be using oil-lubricated journal bearings, which overcomes the problem of bearing life but introduces radial clearances between the journal and the shaft which impact unfavorably on turbomachinery tip clearances and seal clearances. Other problems to be considered would be alignment, starting and shut-down problems, and self-excited instabilities.

Another possible alternative would be gas-lubricated journal bearings. Several major design problems are associated with using air, with its low viscosity, as a lubricant. The very small operating film thicknesses mean that alignment, dimensional stability, thermal distributions, and surface irregularities are critical and starting and stopping are a problem. However, gas bearings reduce oil circulating and cooling requirements, eliminate oil seals, and reduce tip and shroud clearances.

Objective:

The objective of the bearing technology advancement program is to design concepts for relatively small, very high-speed bearings offering high reliability and long life.

Technical Approach:

1. Design and develop a rolling-element bearing for very high speed application, with a DN value greater than $1.8 \times 10^6$ mm-rpm.

2. Design and develop for very high speed applications, alternatively:

   a. an oil-lubricated journal bearing, or
   b. an air-lubricated journal bearing.

## HYDRAULIC PUMPS/MOTORS

### Background and Aims:

The Task IV study clearly establishes that the unreliability of the hydraulic pumps and motors seriously affects the dispatch reliability of the aircraft system when the components are used in either the APU or main engine starting systems. The aircraft's overall mission capability would be advanced by improving the mechanical integrity of the hydraulic pumps and motors.

### Objective:

The objective of the program is to improve the reliability and mechanical integrity of hydraulic pumps and motors used in aircraft systems.

### Technical Approach:

1. Assimilate and collate data on component failures from service and manufacturing organizations.

2. Establish nature, type, and cause of each failure.

3. Determine feasibility of instituting corrective action in either the component design or the application of the component as used in the aircraft.

4. Disseminate the results and recommendations to contracting agencies and to component manufacturers.

PNEUMATIC SYSTEMS

SPS components included among the pneumatic subsystems for which research and development programs were recommended included air turbine starters, cartridge starters, and environmental control systems.

Pneumatic Air Turbine Starters

Background and Aims:

Vendor inquiries conducted under Task I of the program revealed that air turbine starters which have been designed specifically for engines in the desired power class were unavailable. A starter, specifically designed for the anticipated engine, would minimize the air horsepower required for starting and would result in the least component weight.

Expected Benefits

It is estimated that a reduction in APU equivalent shaft horsepower of about 10 is obtainable by optimizing the ATS for the proposed main engine. ATS weight and volume can probably be reduced by 10 percent, resulting in a weight savings of about 2 pounds per aircraft.

Objective:

The objective of the air turbine starter program is to design and develop a pneumatic engine starter specifically for the engines in the required power class.

Technical Approach:

1. Conduct required parametric studies to optimize and to establish the power requirements and nozzle/turbine design criteria for starting the main engines.

2. Synthesize and evaluate design options.

3. Prepare designs.

4. Fabricate prototypes.

5. Conduct laboratory and qualification tests.

Cartridge Pneumatic Starter

Background and Aims:

Task IV revealed significant improvements in aircraft dispatch reliability with the inclusion of a backup main engine starting system. Selection of a pneumatic starting system determines the need for a compatible backup starter. A pneumatic cartridge starter specifically designed for the anticipated engine requirements would provide the least component and system weight.

Expected Benefits:

It is estimated that mission cancellations due to SPS failures can be reduced from approximately 8 to .8 per thousand starts by providing a cartridge pneumatic starter in place of the pneumatic-only starter on one engine. Obtaining this benefit requires development of a cartridge pneumatic starter tailored for the proposed application since no suitably sized units are available.

Objective:

The objective of the cartridge program is to design and develop a cartridge-powered pneumatic engine starter specifically for main engines in the desired power class.

Technical Approach:

1. Conduct required parametric studies to establish and optimize power requirements and cartridge and nozzle/ design criteria for starting the main engines.

2. Synthesize and evaluate design options.

3. Prepare designs.

4. Fabricate and perform laboratory tests.

5. Conduct required qualification tests.

## Environmental Control Systems - Personnel

### Background and Aims:

Present air-cycle machines are designed to operate using air power supplied by an external compressor source. Significant improvements in overall system efficiency may be realized if air-cycle machines could be powered by mechanically driven means.

### Expected Benefits:

The mechanically powered air-cycle machine is expected to require an input of about 15 hp, whereas a bleed air system required appreciably more power. For example, in the proposed SPS, the equivalent shaft horsepower required for bleed air is about 49 for APU bleed and about 45 for engine bleed. The mechanically powered ECS is particularly compatible with the proposed aircraft since the transmission drive source is close to the cockpit area which is to be cooled.

### Objective:

The objective of the personnel ECS program is to determine the feasibility and possible configuration(s) of a mechanically powered air-cycle machine for use in the aircraft environmental control system.

### Technical Approach:

Conduct necessary preliminary conceptual studies and evaluation studies to determine the feasibility of developing air-cycle machines using mechanical means as a primary power source.

## Environmental Control Systems - Avionics

### Background and Aims:

Future avionics components will utilize advanced solid-state techniques and methods, and it is anticipated they will require more exact and stable temperature conditions and contaminant-free environments for operational and endurance capabilities. Thermoelectric cooling systems in closed avionics compartments may prove to be competitive for these advanced avionics compartments. The power requirements and heat rejection rates anticipated for the avionics systems appear to approach present-day thermoelectric cooling system capabilities. Also, the system could provide accurate temperature control within a closed compartment, protected from infiltrated or induced contaminants which could be detrimental to the avionics components.

### Expected Benefits:

Avionics equipment life can be increased by providing the regulated temperature and the freedom from contaminants afforded by a thermoelectric cooling system. Greatly improved cooling reliability is expected since thermoelectric cooling equipment has no moving parts.

### Objective:

The objective of the avionic ECS program is to determine the feasibility of developing thermoelectric cooling systems for closed compartments housing advanced aircraft avionics components.

### Technical Approach:

Conduct preliminary conceptual, parametric and evaluation studies to determine the feasibility of developing thermoelectric cooling systems for the advanced avionics components.

## ELECTRICAL SYSTEMS

Research and development efforts recommended for electrical systems encompassed starter motors, batteries, and generators.

### Electric Motor Starters - Main Engine

#### Background and Aims:

Electric motor starter systems for starting the aircraft main engines were eliminated early in candidate selection trials because of excessive starter motor weights. Task IV revealed that electric motor starting systems for the APU had the best reliability of the three types of systems considered, but that the weights of the motor starter and the battery were high. However, it appears possible that the development of a high-speed (30,000 to 60,000 rpm) electric motor starter would result in appreciable reduction in starter weight, thereby making it competitive for main engine starting. Additional starting system weight savings could be realized by incorporating rectifiers in the starter motor to enable operation directly from the three-phase 115/200-volt ac bus of the aircraft. This would eliminate the need for transformer-rectifier capacity to supply the low-voltage dc normally used for electric starting.

#### Expected Benefit:

The electric motor starter can provide appreciably higher reliability than the pneumatic type. However, existing electric units are much heavier than pneumatic. It is expected that an electric starter development program could result in reduction in weight to the point where the electric starter would be more cost-effective than the pneumatic because of the increased reliability.

#### Objectives:

Determine the feasibility of developing lightweight, high-speed electric motor starters, incorporating rectifiers to enable direct connection to the three-phase 115/200-volt ac power system of the aircraft.

#### Technical Approach:

Conduct necessary conceptual and evaluation studies to determine the feasibility of developing high speed electric

motor starters for use on the aircraft main engines. Analyze effects of starter electric load on the ac generator system.

## Electric Batteries

### Background and Aims:

Power discharge ability of present battery configurations at temperatures lower than -25°F would also prohibit the use of electrical starting systems for APU engines, if the aircraft has mission and storage requirements in such temperature environments. Elimination of this impediment would provide a much more reliable system for starting the APU.

### Expected Benefit:

Obtain a practical battery installation that will serve as an adequate and reliable source of power at low temperatures (below -25°F).

### Objective:

The objective of this battery research program is to investigate methods and materials applicable to high-performance operation of batteries at low-temperature conditions.

### Technical Approach:

1. Conduct study programs to develop criteria establishing maximum low-temperature storage time expected or experienced on Army aircraft.

2. Determine feasibility of utilizing insulation techniques to protect batteries for the time determined above.

3. Investigate means of heating the battery to determine if a heat source can be developed that would be economical and compatible with the aircraft environment and mission.

4. Survey the industry and literature to review material and electrolyte combinations best suited for low-temperature performance.

5. Conduct preliminary studies to determine feasibility, projected weight, and performance of batteries with the selected materials.

## Electrical Generators

Contributing component manufacturers do not anticipate the need for additional funding to achieve the Task IV predicted technological advancements for future electrical generator designs. Considerable development, funded by other programs, is being conducted to expand the generators' capability, utilizing the oil-cooling techniques recently incorporated.

## ENVIRONMENTAL PROTECTION (APU INLET-AIR)

The design configuration for the APU engine and subsystems should provide protection from ingestion of foreign objects, sand and dust, ice, and other debris, with minimal detrimental effects on performance, maintainability, and reliability.

### Background and Aims:

Inlet separator concepts must be developed to afford the desired protection from sand, dust, and foreign objects, achieving minimum loss in performance and no impairment in capability to execute transients.

Anti-icing provisions for all struts, vanes, or housings protruding into the inlet-air stream must be included in the engine design, to permit APU operation without substantial loss in power when meteorological conditions are conducive to icing.

The engine should also perform satisfactorily despite extended operation in salt-laden air. Performance and operating life, between scheduled overhauls, should not be permanently reduced as a result of salt deposits or corrosion of engine parts. This requirement suggests that provisions be incorporated in the design for injecting water and corrosion-inhibiting fluid into the engine for cleaning purposes.

### Objectives:

The objective of this technology advancement program is to define those provisions which should be incorporated into the APU configuration to permit extended operation in adverse environments with minimum losses in performance and operating life.

### Technical Approach:

1. Evaluate separator and filter concepts applicable to the APU, to select optimum system.

2. Define inlet anti-icing requirements, including filter/separator subsystem.

3. Incorporate water-wash provisions in APU front-frame design.

## TIME AND COST ESTIMATES

Estimates of time (expressed in engineering man-hours) and cost (in thousands of dollars) to accomplish these recommended research and development programs and to achieve the desired technology advancements were summarized in Table XLVII. Where applicable, alternative technical approaches were suggested to achieve the desired objectives.

### New or "Off-the Shelf" Systems

SPS weights and costs and the impact on aircraft system weights and costs were compared for an "off-the-shelf" secondary power system and a new system, configuration D. The "off-the-shelf" SPS was the configuration presented in Reference 3, which is pictured in Figure 40. The APU is assumed to be a modified version of an existing unit. This system includes cockpit ECS, but not backup main-engine starting - so configuration D with the corresponding options was used as the basis of the comparison. The weights for the "off-the-shelf" system included:

| | |
|---|---|
| engine start system | 39.6 lb |
| APU and APU start system | 205.0 |
| accessory drive, main gearbox | 48.0 |
| flight control power packs | 23.1 |
| generators and control units | 72.2 |
| ECS | 156.6 |
| Total | 544.5 lb |

(Note: the above weights include installation weights.)

The APU weight included APU-mounted hydraulic pump and ac generator.

Table XLVIII compares the weight and cost parameters for the two systems. The same factor of 2.07, which was used previously, is used to calculate the influence of SPS weight on aircraft takeoff gross weight. Nonrecurring costs of $8.1 million for the configuration D system (including cockpit ECS but not backup engine starting) were obtained from Table XXXVIII. The difference of $3.7 million between the "off-the-shelf" system and this reflected a $3.3 million APU development ($3.5 million is quoted in Table XXXVIII, but $0.2 million was deducted because of required modification of an existing APU unit). An additional $0.4 million was added for the ATM development.

Flyaway costs for the configuration D system (total acquisition cost for the SPS for a 2000-aircraft fleet) were obtained from Table XXXVIII. The flyaway costs for the "off-the-shelf" system

TABLE XLVII. REQUIRED SPS COMPONENT RESEARCH AND DEVELOPMENT

| COMPONENT | TECHNICAL APPROACH/TASK | REQUIRED R&D | | ALTERNATIVE R&D | |
|---|---|---|---|---|---|
| | | M/H | 1000 $ | M/H | 1000 $ |
| APU | 1. Design, develop and qualify APU for SPS requirement (1970 tech) | 150,000 | 3,500 | | |
| APU - Centrifugal Compressor | 1. Minimize tolerances, clearances of centrifugal impeller * | 4,000 | 160 | | |
| | 2. Define bleed configurations | 6,000 | 250 | | |
| | 3. Design, develop variable geometry for compressor | 11,000 | 425 | | |
| | 4. Evaluate abradable materials for tip shrouds, variable vanes | 2,000 | 80 | | |
| | 5. Investigate composites, nonlubricated bearing materials | 4,500 | 190 | | |
| - Radial Turbine | 1. Minimize tolerances, clearances of radial turbine * | 4,000 | 160 | | |
| | 2. Establish stage loading capability | --- | --- | | |
| | 3. Evaluate high-temperature materials * | 12,000 | 440 | 20,000 | 850 |
| | 4. Evaluate cooling concepts * | 8,000 | 360 | | |
| | 5. Design, evaluate variable turbine nozzles | 7,000 | 280 | | |
| - Combustor | 1. Minimize inlet airflow mal-distribution | 1,500 | 70 | | |
| | 2. Improve primary zone mixing * | 3,000 | 130 | | |
| | 3. Improve secondary mixing, turbine-inlet temperature profile * | 2,000 | 80 | | |
| | 4. Minimize film cooling air requirements | 2,500 | 110 | | |
| | 5. Define corrosion-/sulfidation-resistant liner alloys | 3,000 | 120 | | |
| | 6. Determine emulsified fuel requirements | | | 2,000 | 85 |
| - Seals | 1. Define design criteria/recommended practices for contact-type seals | 4,000 | 160 | | |
| | 2. Evaluate design concepts for labyrinth seals | --- | --- | | |
| - Gears | 1. Define, evaluate advanced gear materials for increased load capacity * | 4,000 | 180 | | |
| | 2. Determine new tooth forms for increased load capacity | 2,500 | 100 | | |
| | 3. Improve tooth tolerances, surface finishes * | 5,000 | 200 | | |
| | 4. Evaluate composite reinforced plastics for gear housings | 2,500 | 90 | | |
| - Shafting | 1. Evaluate beryllium properties, perform vibration/shock testing | 6,000 | 240 | | |
| | 2. Investigate machining methods and inspection techniques | 4,000 | 130 | | |
| - Bearings | 1. Design, develop high-speed rolling-element bearing * | 4,500 | 175 | | |
| | 2. Design, develop oil-lubricated/air-lubricated journal bearing | 3,500 | 140 | 7,000 | 265 |
| HYDRAULIC PUMPS | 1. Conduct reliability improvement program | 4,000 | 100 | | |
| ECS<br>1 - Avionics-Compartment Cooling | 1. Conduct feasibility/configuration study for UTTAS avionics-compartment cooling utilizing thermo-electric systems | 4,000 | 100 | | |
| 2 - Air-Cycle Machine (ECS) (Heat exchanger-comp/turb) | 2. Conduct feasibility/configuration study for UTTAS air-cycle machine for cockpit cooling considering recirculation, bootstrap/mech drive-systems * | 4,000 | 100 | | |
| PNEUMATIC SYSTEMS | 1. Design, develop and qualify ATS for UTTAS size engines * | 15,000 | 400 | | |
| ELECTRICAL SYSTEMS | 1. Conduct APU electrical starting system feasibility study.<br>(a) Utilizing hi-speed motor & low temperature battery operation | 4,000 | 100 | | |
| | 2. Conduct main engine electrical starting system feasibility study for UTTAS size engines. | 4,000 | 100 | | |
| CARTRIDGE-PNEUMATIC STARTERS (CPS) | 1. Design, develop and qualify CPS for UTTAS size engines if back-up starting is required. Utilize previous work | 16,000 | 450 | | |
| ENVIRONMENTAL PROTECTION (APU INLET-AIR) | 1. Evaluate/select optimum separator/filter concept for APU * | 1,000 | 25 | | |
| | 2. Define APU-inlet anti-icing requirements | 1,000 | 25 | | |
| | 3. Incorporate water-wash provisions in APU front frame | 500 | 15 | | |
| INFRARED PROTECTION | No requirement - APU not used in flight | --- | --- | | |
| AGB | No requirement - development & research covered under drive systems | --- | --- | | |

* Priority research programs for near-term APU/ATM development.

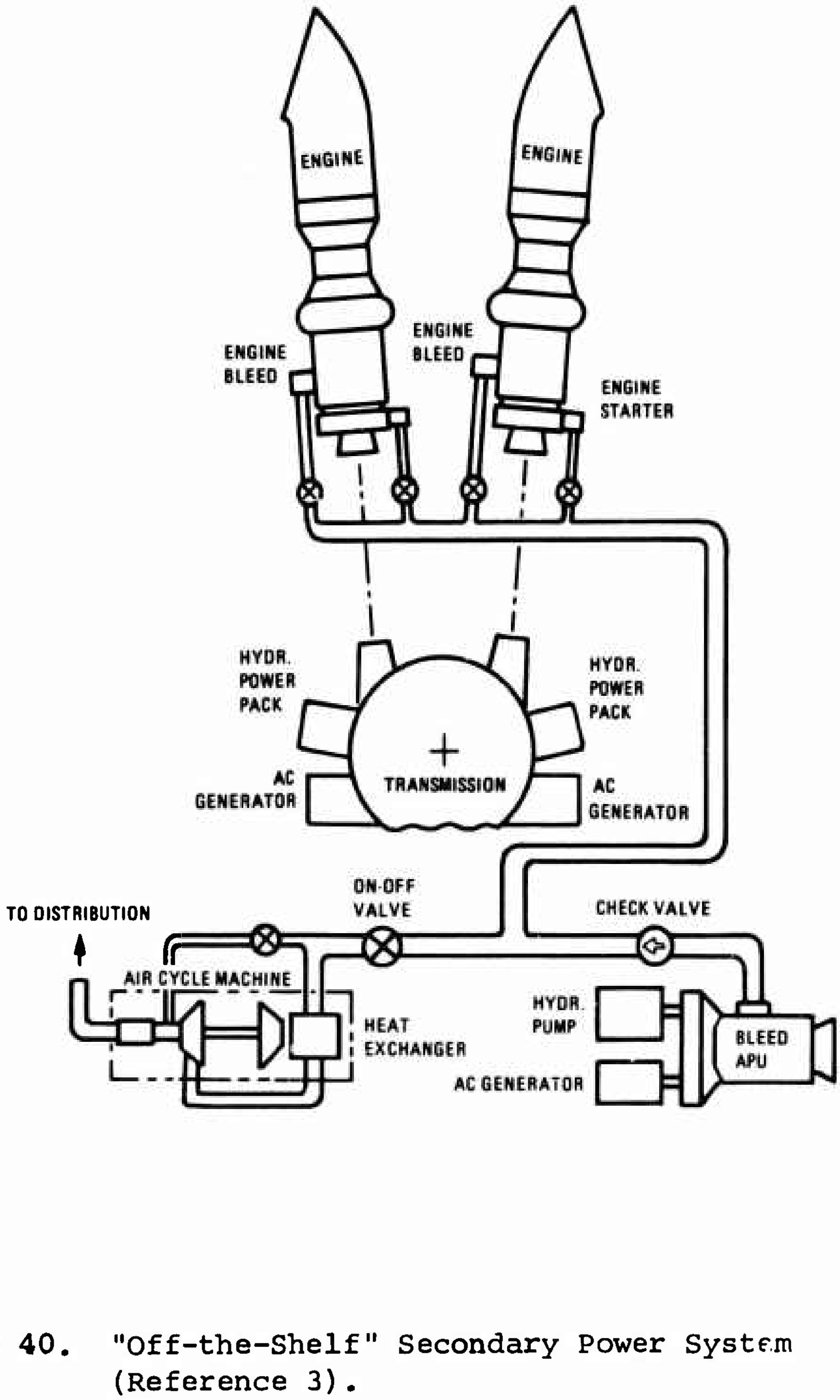



Figure 40. "Off-the-Shelf" Secondary Power System (Reference 3).

TABLE XLVIII. COMPARISON OF "OFF-THE-SHELF" AND NEW SPS

| | SPS Installed Weight (lb) | Aircraft Weight Influence (lb) | SPS Non-recurring Cost $Mil | SPS Flyaway Cost $Mil | Airframe Cost Reduction $Mil |
|---|---|---|---|---|---|
| Off-the-Shelf (Baseline | 544.5 | 1125 | 4.4 | 158 | |
| New System Configuration D) | 497.0 | 1038 | 8.1 | 142 | |
| Change | -47.5 | - 97 | +3.7 | -16 | -21.3 |
| Total Improvement | 97 lb | | | $33.6 Mil | |

included provision for one additional hydraulic pump and one ac generator, but not the AGB cost. Actually, the "off-the-shelf" system was charged with the costs for additional transmission pads and credited with the AGB costs. The airframe cost reduction was a direct function of the reduced TOGW and was calculated at $110 per pound of aircraft weight. (Total improvement is 97 pounds in aircraft system weight and $33.6 million in life-cycle cost for the 2000-aircraft fleet). An estimated program schedule for an APU developed specifically for the SPS is pictured in Figure 41, and indicates that three years would be required to achieve production status.

## Near-Term Research and Development

Table XLVII is a comprehensive list of recommended research and development programs to accomplish the desired technological advancements in SPS components and to achieve significant system improvements, culminating in the development of an auxiliary power unit and air turbine starter applicable to the helicopter requirement. From Table XLVII were selected those R&D programs, in whole or in part, applicable to a near-term APU/ATM development and a near-term (approximately 1975) secondary power system (note the items marked with an asterisk in the table). Such a list of recommended near-term research effort would include:

1. Define high-performance centrifugal compressor concepts compatible with capabilities and limitations of production methods ($160,000).

2. Conduct a similar program for radial turbines ($160,000).

3. Evaluate high-strength nickel-base cast and forged alloys and internal cooling concepts for cooled, high-temperature radial turbines ($250,000).

4. Determine satisfactory concepts for improved flame distribution and combustion- /secondary-air mixing to achieve desired turbine-inlet temperature profile ($210,000).

5. Define advanced gear materials and improvements in tolerances and surface finishes for increased loading, reduced wear ($200,000).

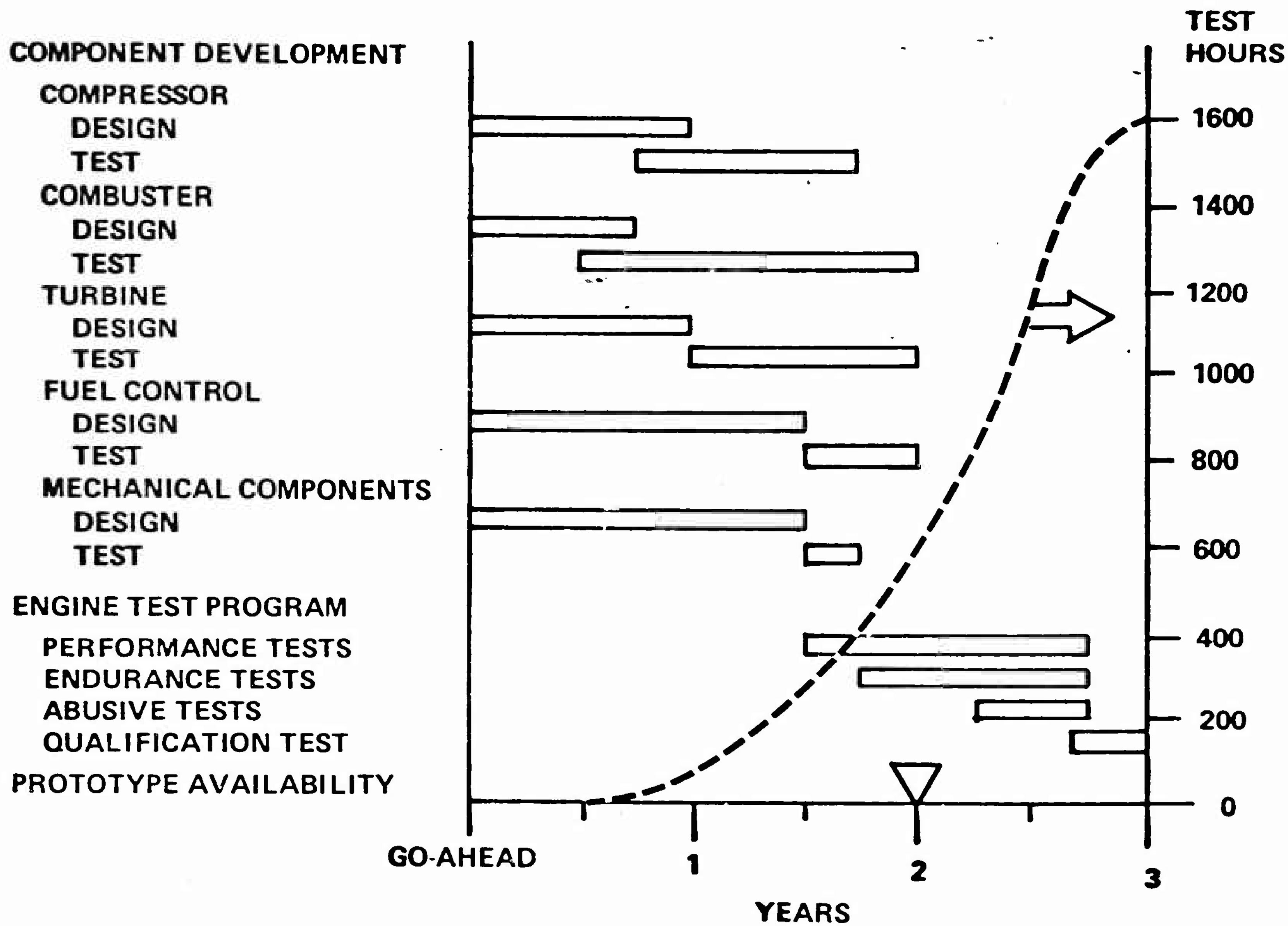



Figure 41. APU Development Program Schedule.

6. Design rolling-element bearings for very high-speed application ($100,000).

7. Determine possible improvements in hydraulic pump and motor reliability ($100,000).

8. Conduct conceptual studies and evaluation studies of mechanically powered air-cycle machines for ECS ($100,00).

9. Evaluate APU-inlet separator/filter concepts for protection from sand and dust and FOD ($25,000).

These research programs, which total $1,305,000, could culminate in a development program for an APU sized for the helicopter - in the mid-1970 time frame. The APU development program would be estimated to cost an additional $3,000,000.

## CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations are based on the study.

1. A secondary power system in accordance with configuration D (reference Figure 2) is optimum for the proposed application. This includes a single-shaft APU mounted on and driving directly into the accessory transmission. Both shaft power and bleed air power are supplied by the APU. Based on parameter cycle study, the following thermodynamic design parameters are recommended:

| Level of Technology | Compressor Pressure Ratio | Turbine-Inlet Temperature - °F |
|---|---|---|
| Existing | 4:1 | 1800. |
| 1975 | 6:1 | 2000. |
| 1985 | 8:1 | 2250. |

These design-point pressure ratios and temperatures result in specific powers and SFC's which are very nearly optimum. Furthermore, the pressure ratios are consistent with the capability of single-stage centrifugal compressors and radial turbines projected as a function of the level of technology, and consequently offer simplicity in the APU design. Among the considerations that led to selection of configuration D are the following:

a. An ATS was selected for main-engine starting because it offered the advantages of low weight, small size, and high dispatch reliability; it used a nonflammable power transfer medium; and inflight re-starts could be achieved by bleed from the operating engine.

b. Hydraulic APU starting provided all-weather capability with unlimited multi-start capacity.

c. The single-shaft APU was the least costly and most reliable of the candidates, and the weight penalty due to driving the AGB during starting was slight.

d. The selection of an air-cycle machine for environmental control was based on superior reliability and minimum weight.

2. Significant cost and weight savings (reference Table XLVIII) can be realized by developing components that are tailored to the SPS requirements and that incorporate latest state-of-the-art advances. It is therefore recommended that research and development be accomplished to insure availablity of suitable components on a timely basis.

3. If backup starting is provided, it is recommended that a cartridge-pneumatic starter be substituted for a pneumatic-only starter on one engine. The other engine would then be started from engine cross-bleed.

4. The SPS, as proposed, is adequate to supply power during an in-flight emergency since accessory drive power is taken from the aircraft rotor transmission which continues turning during flight whether or not main engine power is available.

5. In-flight operation of the APU is not economically justifiable since fuel consumption attributable to SPS is less for transmission drive than for APU drive.

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# ...X I

## PARAM... APU CYCLE STUDY

Task II of the SPS program was a parametric APU cycle study to determine comparative design-point performance for non-regenerative and regenerative engines. Consistent values of pressure losses, component efficiencies, parasitic airflows, and accessory powers, obtained from analyses of selected engines covered in the Task I survey and presented in this Appendix, were used to generate overall performance consistent with the trends of specific power and SFC for the survey engines.

Bleed-air capability of the parametric engines (with zero shaft power output) was expressed as a fraction of inlet airflow. This Appendix also describes the method used to convert shaft-power performance to bleed performance.

### COMPONENT PERFORMANCE

Compressor and turbine efficiencies and turbine cooling-air requirements used in the parametric study were correlated as a function of significant thermodynamic parameters, while representative values for other efficiencies, pressure losses, parasitic airflow, and accessory powers were selected and tabulated. The component performance assumptions all reflect the anticipated small size of the APU engines.

#### Compressor Performance

Compressor adiabatic efficiency was plotted as a function of pressure ratio in Figure 42. Trends for single-stage and two-stage centrifugal compressors were reproduced from Reference 1 together with the assumed trend adopted in that reference for a 1970-technology APU compressor. Points for single-stage centrifugal(C), two-stage centrifugal (2C), and axial-centrifugal (A,C) compressors, obtained from design-point performance analyses of various manufacturers' individual engine models, were spotted on the graph. From Reference 5 were obtained the data for single-stage centrifugal compressors with efficiencies of .818 and .813 at pressure ratios of 5.4 and 6, respectively. These data should be representative of the level of component technology available for advanced small engines, although efficiencies must be reduced somewhat in determining guaranteed specification performance.

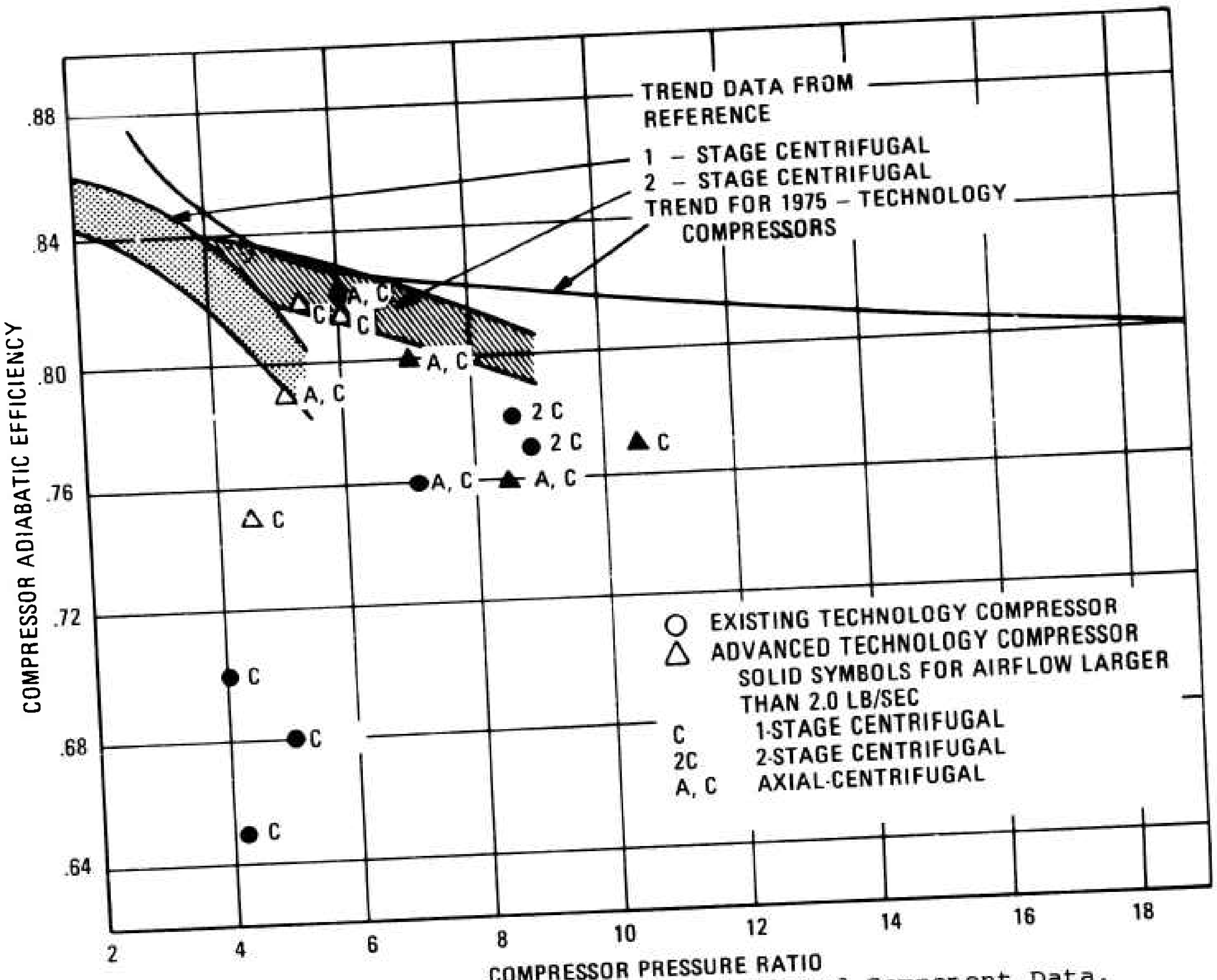



Figure 42. Published Trend Data and Calculated Component Data, APU Compressor Design-Point Efficiencies.

From the data in Figure 42 were developed the trends of compressor performance selected for the parametric APU cycle study, pictured in Figure 43. Centrifugal compressors for existing machines, particularly in the small sizes envisioned in this study, have very low efficiencies. Small axial-centrifugal compressors utilizing existing technology would have improved efficiencies. Projecting improvements in compressor technology to the 1975 production date should produce improved efficiencies as pictured in Figure 43. In addition, Figure 43 shows the anticipated improvements in component efficiency beyond 1975 to the 1985 production date, but major changes are expected also in higher component loadings and larger power-to-weight ratios due to materials improvements.

For the small engines envisioned in this application, pressure ratio may be limited due to its impact on the size of the flow passages at the exit of the compressor. High compressor pressure ratio is desirable from the standpoint of best SFC, but in small engines it is necessarily accompanied by a small compressor exit flow-passage area. In the small passage area, clearances and boundary-layer growth become a significant factor and can lead to increased losses, negating the benefits of high pressure ratio.

To define this limit, a study was undertaken to calculate exit passage dimensions of the centrifugal compressor as a function of airflow, for centrifugal compressors to pressure ratio 12, and axial-centrifugal compressors to pressure ratio 20. Aerothermodynamic relationships were used to determine centrifugal compressor tip speed, and classical specific speed relationships to establish rpm. Tip diameter and flow properties produced the passage width-airflow relationship. A limit of 0.150 inch was established for the centrifugal compressor blade height. With the axial running clearances that can be achieved between the impeller and the stationary impeller shroud, this represents a lower limit on blade height to produce the assumed design efficiencies. At smaller blade heights, blade-thickness requirements and tolerances on blade thickness and shape probably are beyond present-day fabrication capabilities. Within this limit of 0.150 inch blade height, compressor pressure ratios of 20 are satisfactory for air flows as low as 1.0 lb/sec.

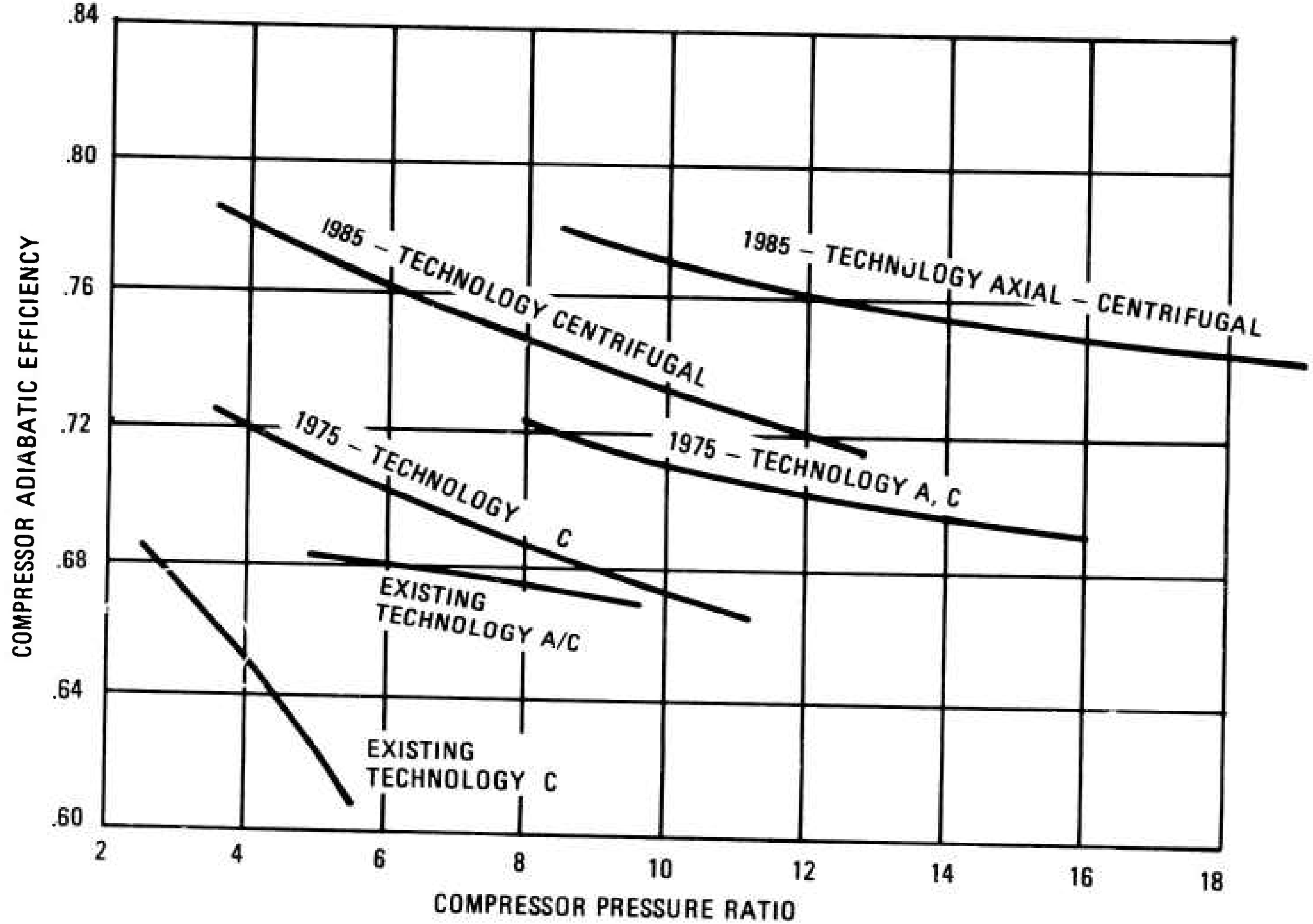



Figure 43. Assumed Compressor Design-Point Efficiency Trends for Parametric APU Study.

## Turbine Performance

In Figure 44, efficiency for single-stage and two-stage axial turbines was plotted as a function of pressure ratio. Trends for two-stage turbines from Reference 1 indicated a high potential efficiency, but points plotted for individual engines seemed to be generally less optimistic. The turbines in existing small APU's are generally radial-flow machines and were not included in these curves. Although the data sample is very limited, the trend curves generated in Figure 44 for existing technology and advanced technology turbines were in agreement with accepted empirical trends and seemed to represent the available data.

Converting the efficiencies in Figure 44 into trend data for the parametric APU cycle study presented difficulties, because of the discontinuous steps which occurred when the number of turbine stages increased from two to three and finally to four, as illustrated in Figure 45. To insure consistent trends in the final APU-engine performance, turbine efficiency for existing-technology machines was assumed to be 0.84, and 0.86 for advanced-technology turbines.

## Turbine Cooling Air

Cooling air required for turbine blades, vanes, and disks, expressed as a percentage of compressor inlet air, was plotted in Figure 46. Trend data from References 1 and 6 were presented. The relationship assumed in the parametric APU cycle study was very similar to these trends.

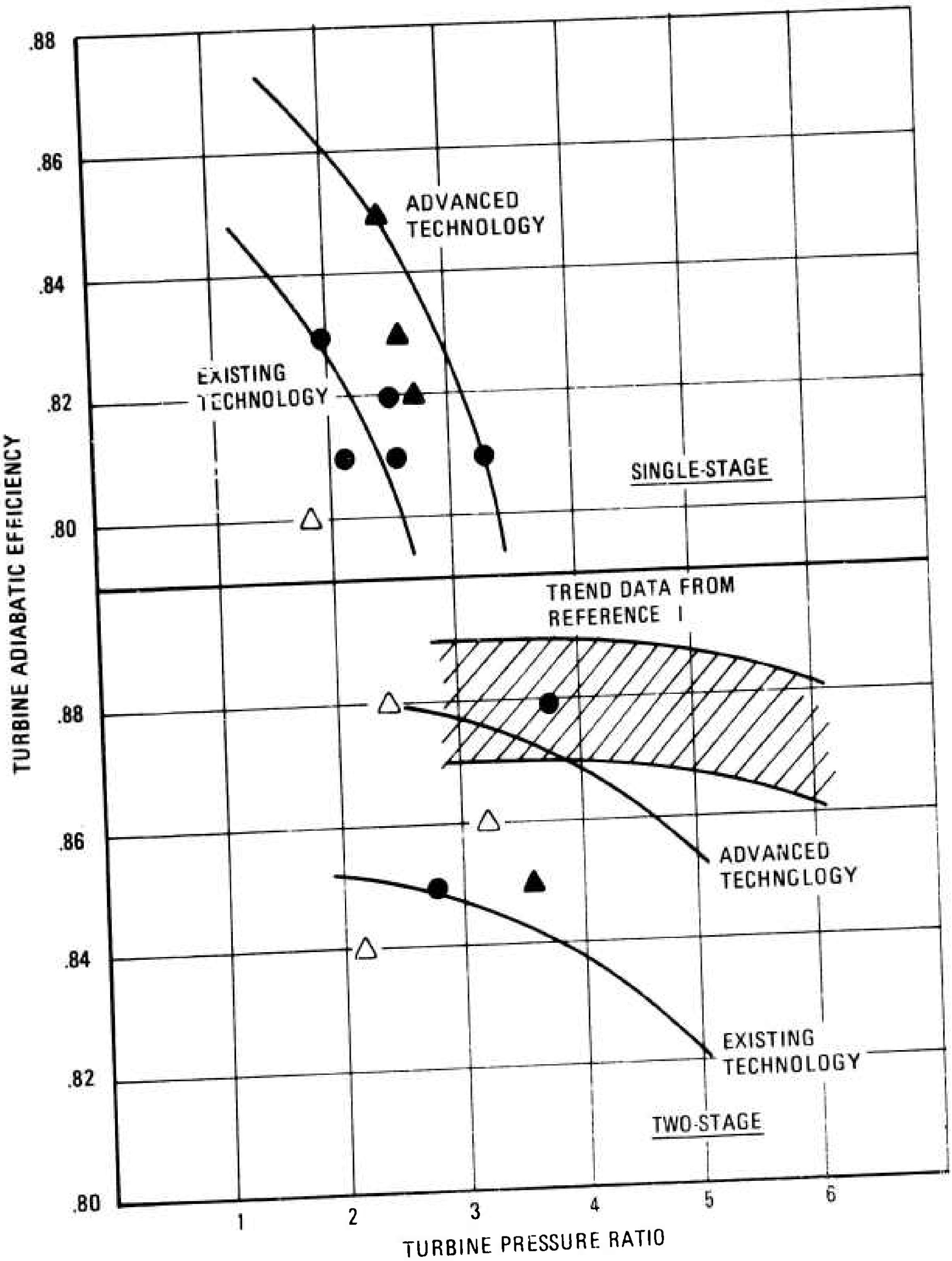



Figure 44. Published Trend Data and Calculated Component Data, APU Turbine Design-Point Efficiencies.

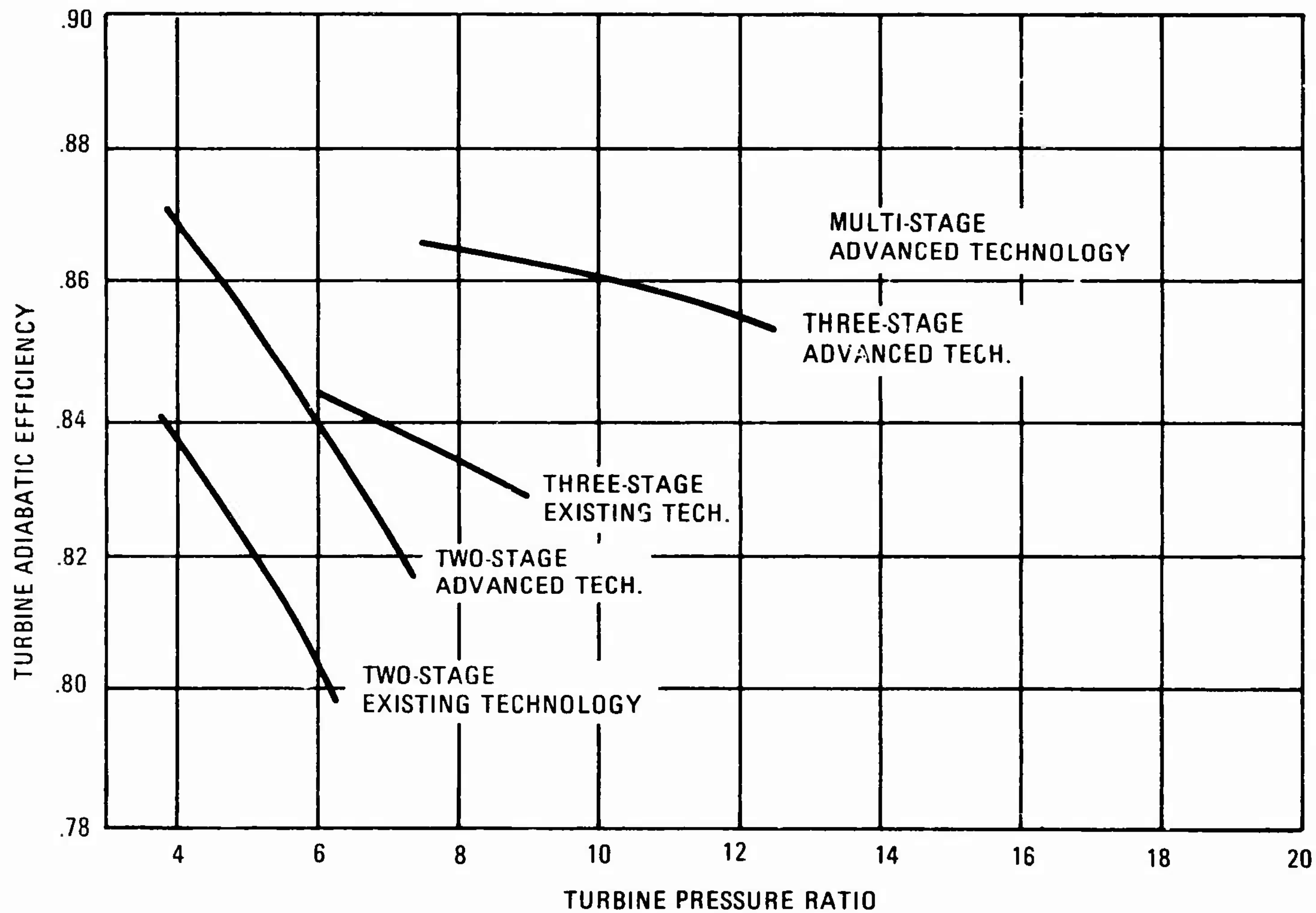



Figure 45. Assumed Turbine Design-Point Efficiency Trends for Parametric APU Study (Existing/Advanced Technology Multi-Stage Turbines).

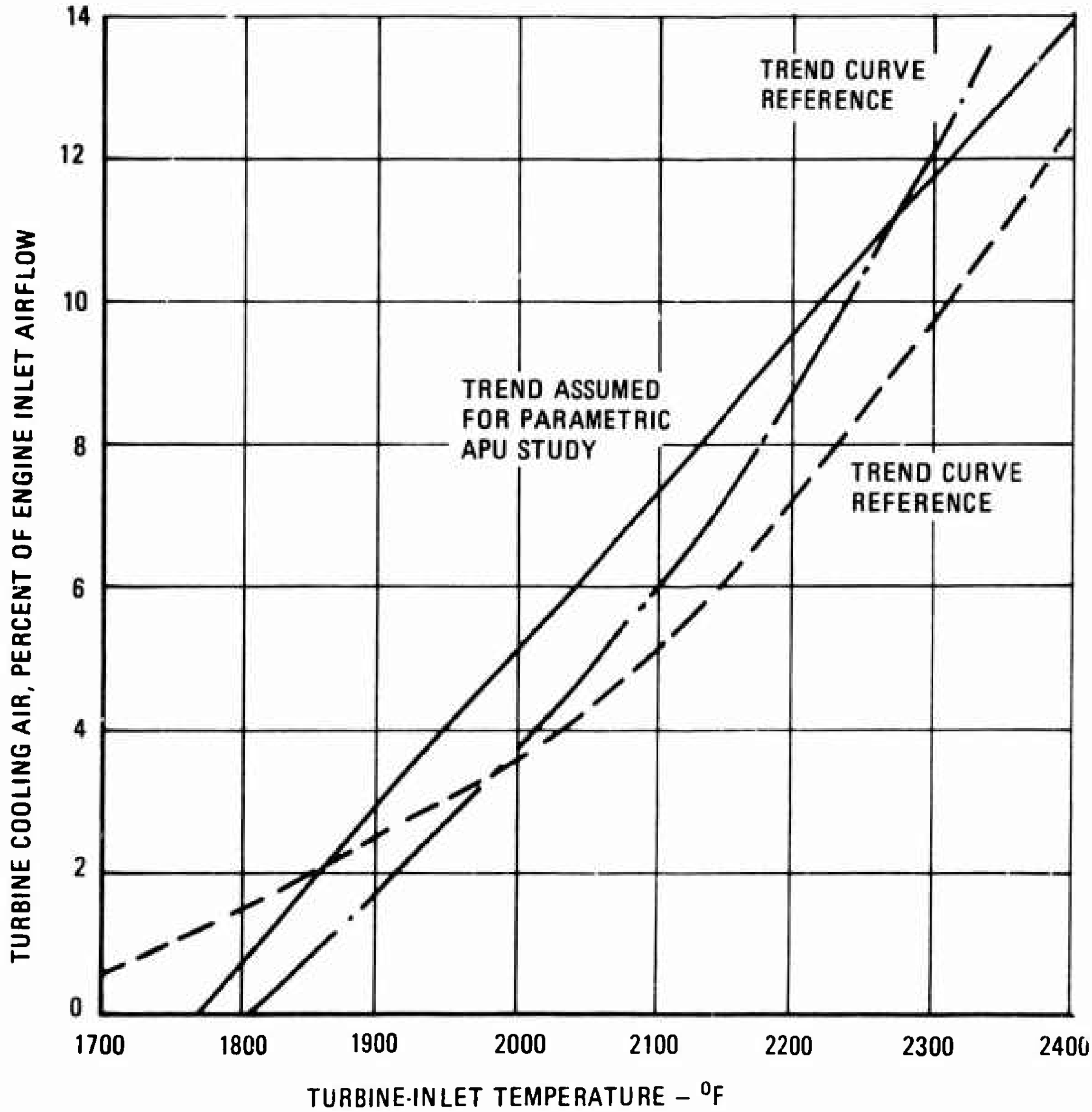



Figure 46. Trend Data for APU Turbine Cooling-Air Requirements.

### Additional Loss Assumptions

Selected values for other component efficiencies, pressure losses, parasitic airflows, and power losses were tabulated in Table XLIX.

TABLE XLIX. COMPONENT EFFICIENCIES AND LOSSES

| | |
|---|---|
| Combustor efficiency | 0.98 |
| Combustor pressure drop, % | 4.0 |
| Fuel lower heating value, Btu/lb | 18400 |
| Losses and accessory power, % | 1.0 |
| Leakage flow, % | 0.5 |
| Exhaust diffuser total-to-static pressure ratio | 1.04 |
| Output shaft gearbox loss, % | 2.0 |
| Regenerative Engines | |
| Air-side pressure drop, % | 4.0 |
| Gas-side pressure drop, % | 5.0 |
| Regenerator leakage, % | 5.0 |

## BLEED-AIR PERFORMANCE

Performance of the parametric engines as bleed APU's, with no shaft-power output, was expressed in terms of the ratio of maximum bleed airflow divided by compressor inlet airflow.

### Bleed Pressure Ratio

Air for the SPS pneumatic components may be supplied by bleed from the APU compressor or by a separate APU-driven load compressor. In either case, a practical limit to the pressure ratio of the air in pneumatic ducts is defined by the maximum allowable air temperature. Although for military aircraft there is no established limit to the temperature in SPS pneumatic ducts, 450°F is a generally accepted limit in commercial aircraft. Temperatures in excess of 450°F pose a fire hazard in the event of a duct puncture in proximity to lubricating oil. The limiting air temperature in the ducts, in conjunction with the ambient temperature at the design point, and a reasonable value of efficiency for the compression process to the bleed port define the allowable pressure ratio of the air supply. Figure 47 shows that a pressure ratio of 4.0 is approximately correct for the 130°F ambient temperature.

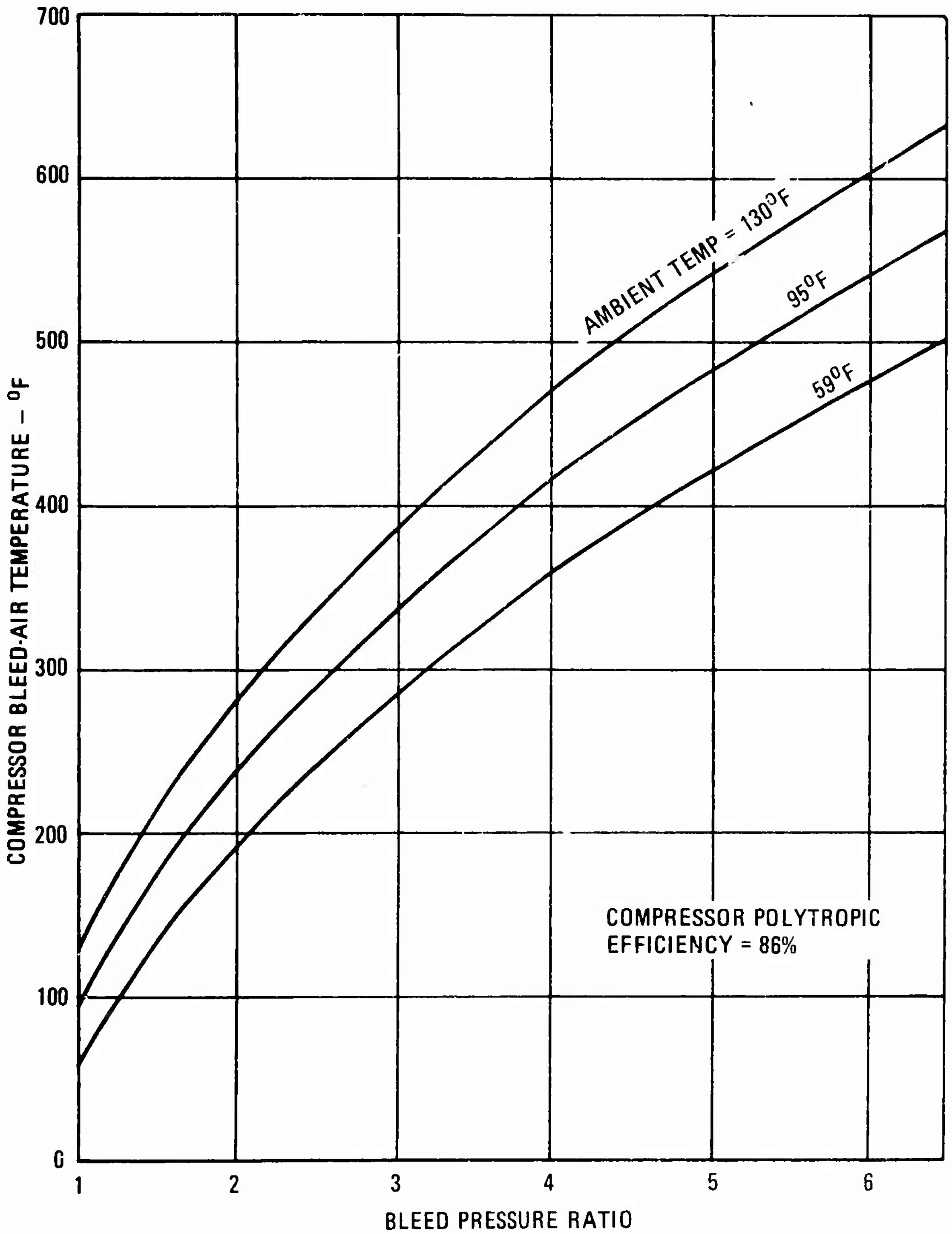
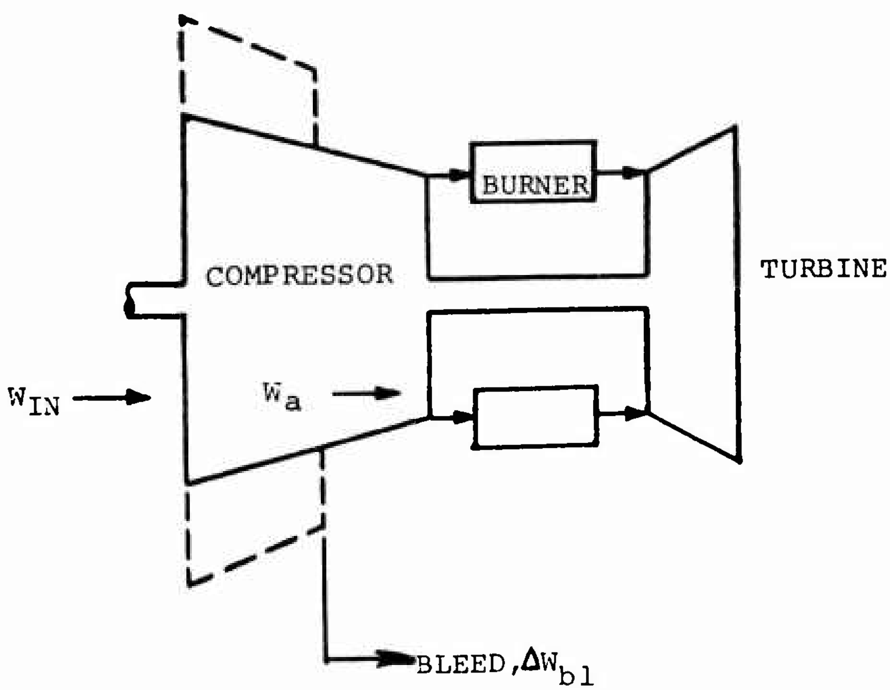



Figure 47. Compressor Bleed-Air Properties.

A bleed-air pressure ratio of 4.0 was selected for the design-point performance calculations of the parametric engines. In those APU engines with a higher design pressure ratio, this would entail an interstage bleed arrangement. However, such an arrangement would be of advantage from the viewpoint of performance, for the engine would have to provide only the work of compression to the interstage bleed port and not to the compressor exit.

The sketch below illustrates schematically the bleed-APU configuration, and the accompanying text describes the method used to convert shaft-power performance to bleed capability, expressed in terms of bleed airflow divided by engine inlet airflow.




$$1.414 \times \frac{\Delta W_{bl}}{W_a} \times \Delta h_{bl} = \frac{1}{\eta_{GEAR}} \times \frac{SHP}{W_a} \times \eta_m \tag{1}$$

where SHP = power output of a shaft power APU (hp) sized for $W_a$ = compressor-inlet airflow (lb/sec)

$$\text{Therefore, } W_{IN} = W_a + \Delta W_{bl} \tag{2}$$

$$\frac{\Delta W_{bl}}{W_a} = \frac{\Delta W_{bl}}{W_{IN} - \Delta W_{bl}} = \frac{1}{\frac{1}{\frac{\Delta W_{bl}}{W_{IN}}} - 1} \tag{3}$$

$$\frac{\Delta W_{bl}}{W_{IN}} = \frac{1}{1 + \frac{1}{\frac{\Delta W_{bl}}{W_a}}} \tag{4}$$

$$\frac{\Delta W_{bl}}{W_{IN}} = \frac{1}{1 + \frac{\frac{1}{\eta_m \times \frac{SHP}{W_a}}}{\eta_{GEAR} \times 1.414 \times \Delta h_{bl}}} \tag{5}$$

APPENDIX II

LOADS ANALYSES

This appendix contains the load analyses which determined the SPS power requirements. Hydraulic power requirements and pneumatic power for ECS were assumed to be the same as those developed previously and documented in Reference 3. Electrical loads are analyzed in considerable depth.

ELECTRIC LOAD FOR ENGINE START AND GROUND CHECKOUT

Continuous electrical loads include:

| | |
|---|---|
| Engine Instruments | .20 kva |
| Interphone | .03 |
| Cockpit Lights | .30 |
| Battery Charge | .20 |
| Warning System | .08 |
| Miscellaneous Relays | .10 |
| T-R Unit Losses | .50 |
| Total | 1.41 kva |

Additional loads for engine start are:

| | |
|---|---|
| Boost Pumps | 1.2 kva |
| Engine Control | .3 |
| Total | 1.5 kva |

Ground Check Loads

Loads other than the above continuous loads are assumed to be turned on only as required for ground check, up to a total of 5 kva. Following are examples of ground check loads:

| | |
|---|---|
| Windshield Heat (Test Mode) | .6 kva |
| Blade De-ice (Test Mode) | .8 |
| Boost Pump | .6 |
| HP Radio | .3 |
| External Light | .5 |
| IFF | .2 |

## INFLIGHT ELECTRIC LOADS

Inflight electric loads include:

| | | |
|---|---|---|
| Battery Charge | 5.0 amps DC | |
| Engine Transmission Instruments | 1.0 | 200 va AC |
| Fuel Boost Pumps | .8 | 2,300 |
| Engine Control | 2.0 | 200 |
| SAS/ASE (Stability Augmentation System/Auto. Stabilization Equipment) | 6.0 | |
| Pitot Heat | | 110 |
| Yaw Port Heat | | 300 |
| Avionics | 21.3 | 1.039 |
| Land, Hover, & Searchlights | 1.5 | 900 |
| Anticollision Lights | | 240 |
| Navigation Lights | 3.0 | |
| Cockpit Lights | 5.2 | 300 |
| Cabin Lights | 2.0 | |
| Hoist Control | .4 | |
| Windshield Wipers | 8.0 | |
| Windshield Heat | | 6,000 |
| Blade De-Ice | | 11,000 |
| T-R Units | | 2,100 |
| | 56.2 amps DC | 24,689 va AC |

Possible additional loads are LORAN, Doppler, Terrain Radar, Landing Assist Night Vision Device, Gunfire Detection, Hoist Motor, Engine Inlet Anti-Ice, and Vent Blowers.

The avionics loads are listed below:

| | | |
|---|---|---|
| Heading-Attitude Ref. System | | 100 va AC |
| Map Display | 3.6 amps DC | |
| Head-up Display | .7 | 150 |
| Navigation Computer | | 145 |
| LF-ADF | 1.2 | |
| VOR-LOC | 1.5 | 16 |
| DME (Tactical Precision Approach) | | 50 |
| Radar Altimeter | | 100 |
| UHF-FM(2) | 1.3 | |
| VHF-AM | .6 | |
| UHF-AM | 1.2 | |
| MF-HF-SSB (provisions) | | 333 |
| Interphone | 1.0 | |
| Voice Security (provisions) | 5.0 | |
| IFF | 2.5 | 95 |
| Voice Warning & Recorder | 2.4 | |
| Static Electricity Dissipator | | 50 |
| | 21.0 amps DC | 1,039 va AC |

## APPENDIX III

## APU CONFIGURATION SELECTION DATA

The data in this appendix was generated to support APU configuration selection, and includes a discussion of fluid coupling requirements, APU weights, and APU starting.

### FLUID COUPLING

The fluid coupling was designed to be integral with the APU output gearbox, operating at 20,000 rpm and transmitting 17 hp. It contains a centrifugal clutch which locks in when input and output torques are equal. A solenoid-operated fill valve is activated at 95 percent engine speed, using a speed switch, and the APU-engine lube oil and pumping system are used to fill the coupling.

The dimensional design parameters for the fluid coupling were developed by scaling a 280-hp design, which had a 4.0 in OD and a 1.5-in ID:

$$HP = \left(D_{OD}^{5} - D_{ID}^{5}\right) N^{3} \qquad (6)$$

The result was a 1.25-in ID and a 2.37-in OD coupling, which weighed 2.0 lb. For calculation of starting characteristics, the inertia of the vaned impeller was estimated to be .00007 slug-ft$^2$.

### APU WEIGHTS

The weights defined for the APU's presumed hydraulic starting and included the basic APU weight plus starter, accumulator, electric motor and pump, and controls (Table XL).

| TABLE L. APU WEIGHTS | | |
|---|---|---|
| | Weight - lb | |
| **Single-Shaft APU** | | |
| APU Weight | 87.0 | |
| Starter Motor | 6.8 | |
| Accumulator | 10.1 | |
| Oil | 1.9 | |
| Electric-Motor Pump | 3.6 | |
| Controls | 3.1 | |
| Total | | 112.5 |
| **Single-Shaft APU With Fluid Coupling** | | |
| APU Weight | 87.0 | |
| Fluid Coupling, Oil, Controls | 4.0 | |
| Starter Motor | 4.0 | |
| Accumulator | 6.6 | |
| Oil | .9 | |
| Electric-Motor Pump | 3.6 | |
| Controls | 3.1 | |
| Total | | 109.2 |
| **Free-Turbine APU** | | |
| APU Weight | 113.0 | |
| Starter Motor | 4.0 | |
| Accumulator | 6.6 | |
| Oil | .9 | |
| Electric-Motor Pump | 3.6 | |
| Controls | 3.1 | |
| Total | | 131.2 |

## APU STARTING

The gas generator drag torque and polar moment of inertia of the free-turbine APU were assumed to be equal to the published characteristics of an 85-hp free-turbine starter engine, and the characteristics of the single-shaft APU were assumed to be the same. The starter motor was mounted on an 8000-rpm pad, with 2250-rpm cutoff speed.

The starting system was sized for -65°F operation, neglecting line losses from the accumulator to the motor. From a review of known engine characteristics, it was determined that the

drag torque at -65°F was approximately 2.3 times the drag torque at 59°F and this factor was used to calculate the characteristics for -65°F starting. For -65°F operation, the effect on starting time due to the increased torque developed by the APU after self-sustaining speed is reached was not large relative to 60°F operation. This study assumed that all increase in starting time at -65°F was due to the increase in drag torque before self-sustaining speed was reached.

The accumulator design was based on 4000 psig for full charge and 800 psig for depleted charge.

Figures 48 through 50 show the drag torque-speed characteristics for the single-shaft APU with a fluid coupling, the free-turbine APU, and the single-shaft APU directly coupled to the AGB.

Single-Shaft APU With Fluid Coupling

The calculated windmill drag of the fluid coupling impeller rotating in air was insignificant, and so the drag of the APU to light-off speed was assumed to be the same as the free-turbine gas generator.

Accumulator-motor characteristics:

Total volume - 46 $in.^3$
Precharge - 800 psig at 60°F or 607.7 psig at -65°F
Full charge - 4000 psig at -65°F
Gas volume at -65°F and 4000 psig, $V_i = 22.28$ $in.^3$
Motor displacement (based on initial torque-12 lb-ft, Figure 48),

$$d = \frac{24\pi\tau}{P} = .226 \text{ in.}^3/\text{rev} \tag{7}$$

Rated motor power = 18.3 hp (corresponds to 4-lb motor weight)

Moment of inertia for APU and fluid coupling impeller, $I = .10697$ slug-ft$^2$

Time increment to accelerate shaft speed $\Delta N$ rpm,

$$\Delta t = \frac{2\pi I \Delta N}{60(\tau_{s_{av}} - \tau_{e_{av}})} \tag{8}$$

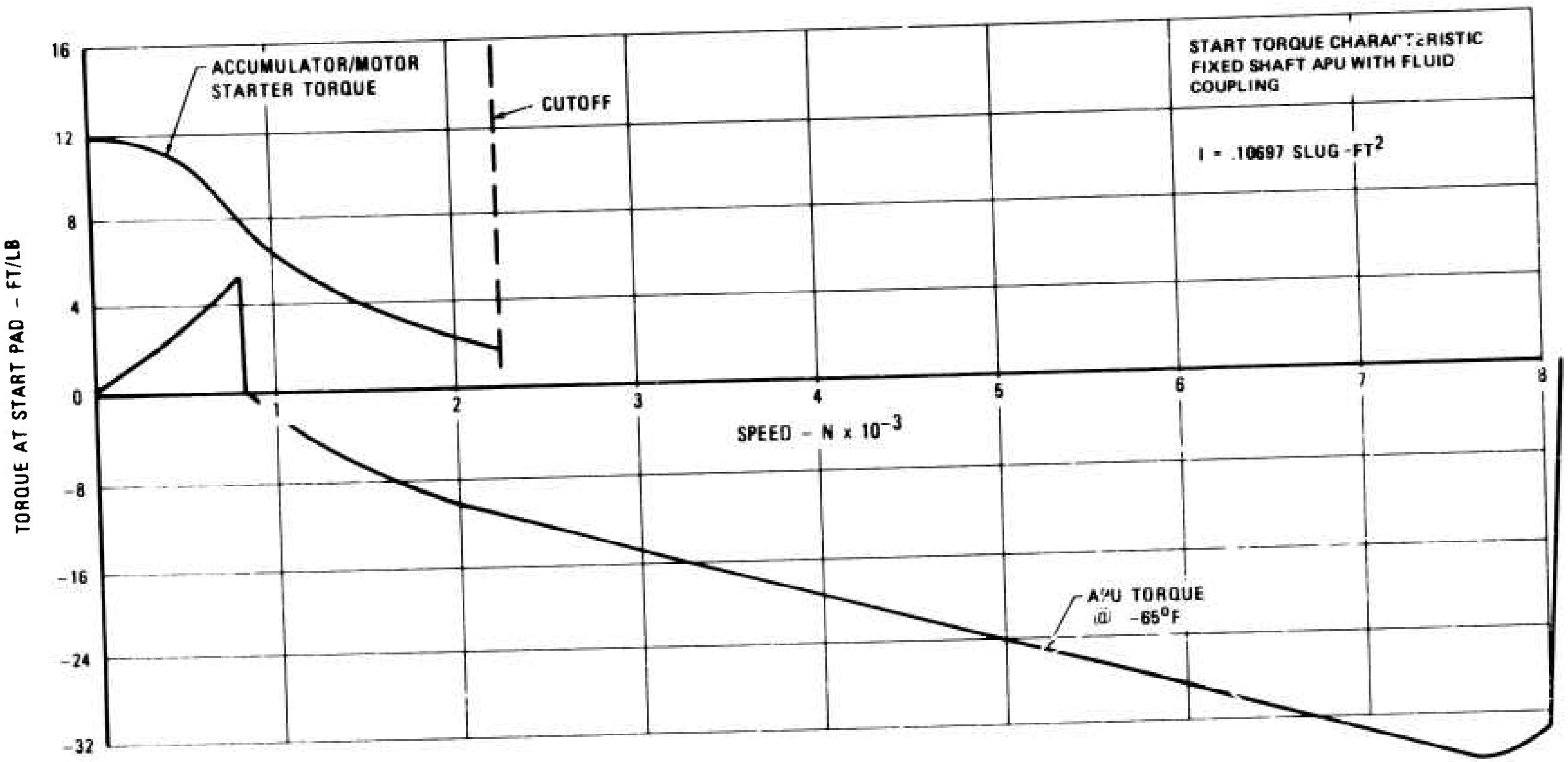



Figure 48. Starting Torque-Speed Characteristics for Single-Shaft APU With Fluid Coupling.

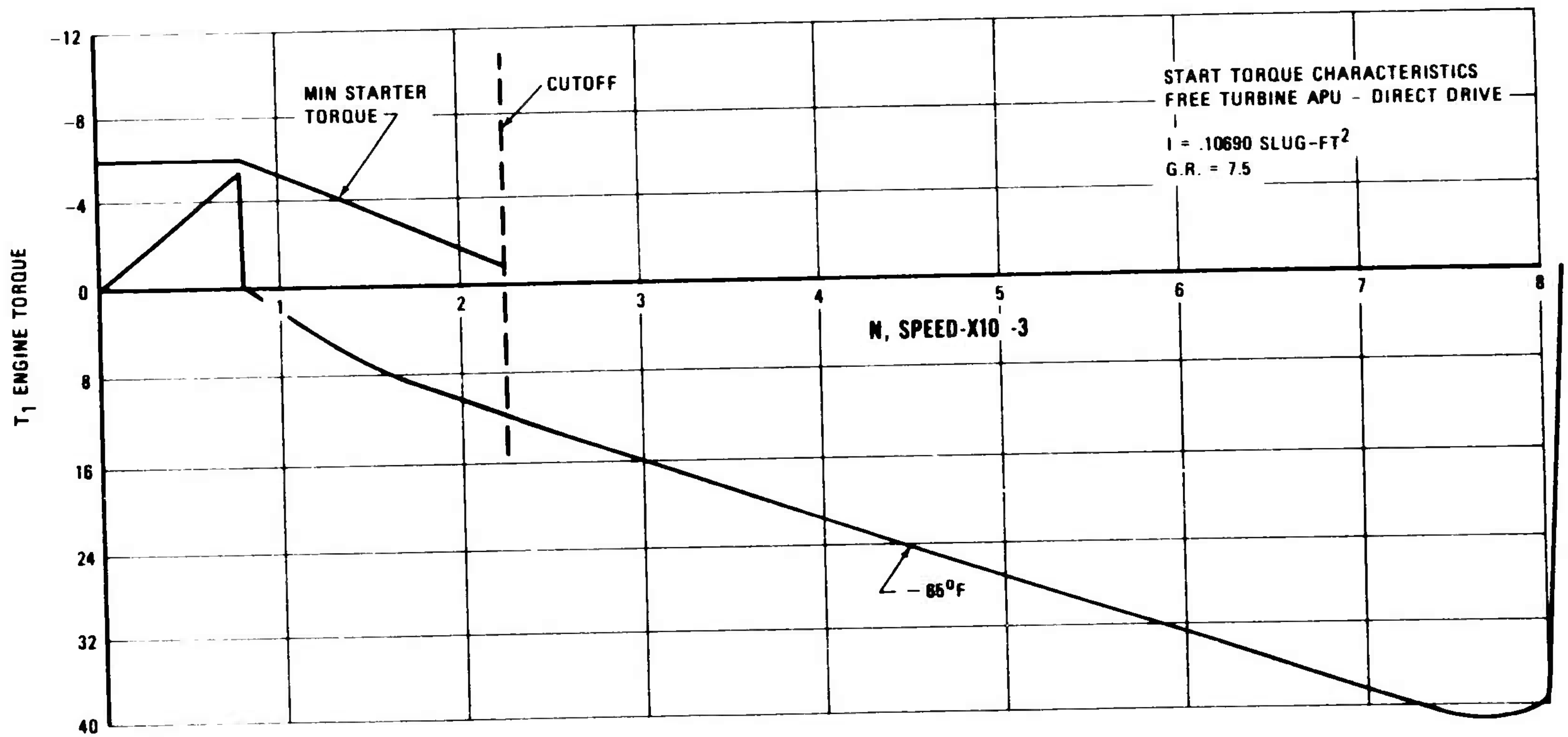



Figure 49. Starting Torque-Speed Characteristics for Free-Turbine APU.

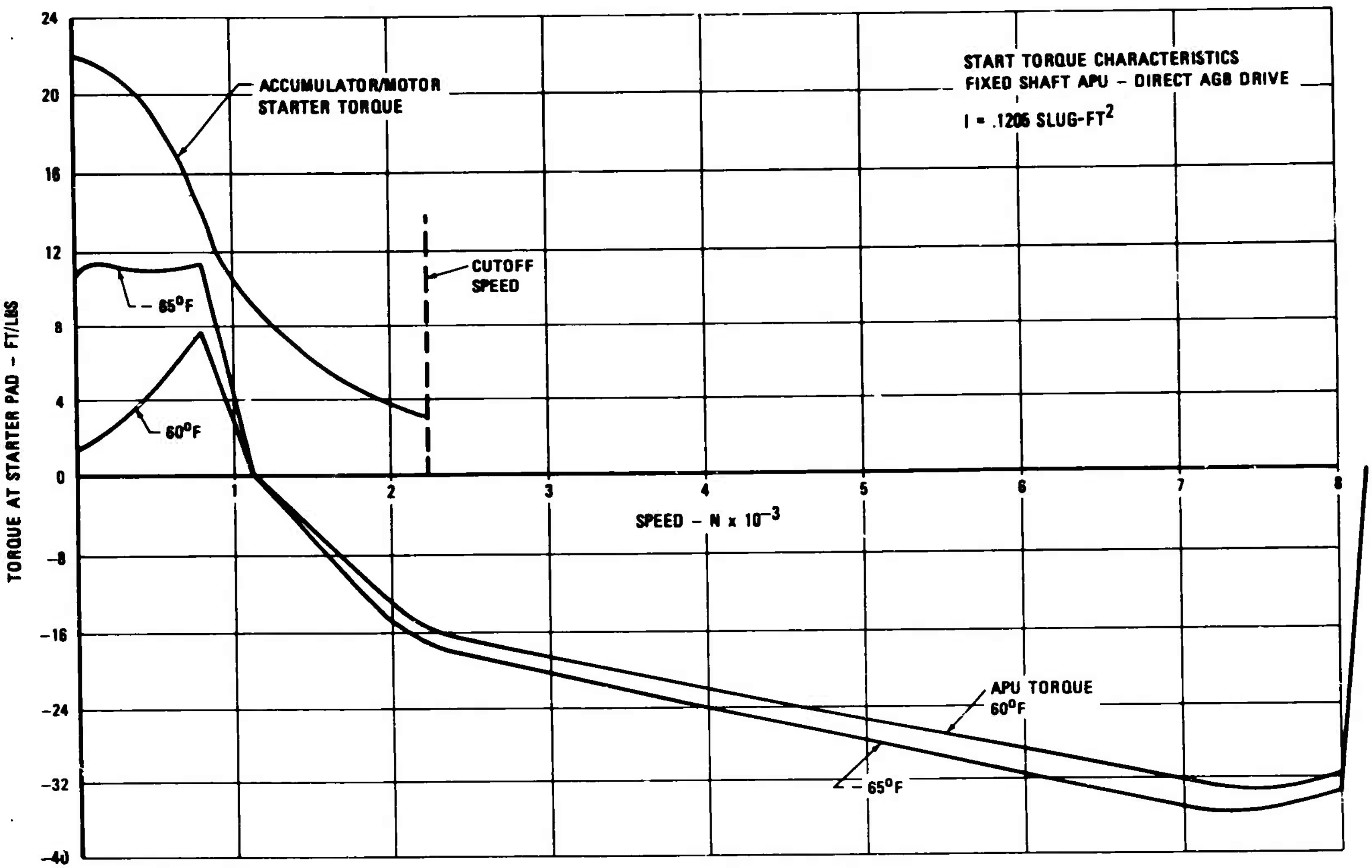



Figure 50. Starting Torque-Speed Characteristics for Single-Shaft APU Directly Coupled to the AGB.

where $\tau_{s_{av}}$ = average starter torque during interval $\Delta N$

$\tau_{e_{av}}$ = average drag torque during interval $\Delta N$

Starter torque at the end of the interval,

$$\tau_{s_2} = \frac{P_i d}{24\pi} \left[ \frac{V_i}{\frac{d}{60} N_2 \sum_o^N \Delta t + V_i} \right]^k \qquad (9)$$

where subscript i is for initial conditions. At -65°F and 800 to 4000 psig, average k was 2.6.

Calculated torque characteristics and starting times were listed in Table LI, and the hydraulic motor torque characteristic was plotted in Figure 48.

TABLE LI. STARTING TIME FOR SINGLE-SHAFT APU WITH FLUID COUPLING

| N1 rpm | N2 rpm | $\tau_{s_1}$ lb-ft | $\tau_{s_2}$ lb-ft | $\tau_{e_{av}}$ lb-ft | $\Delta t$ sec | $\Sigma\Delta t$ sec | Check $\tau_{s_2}$ lb-ft |
|---|---|---|---|---|---|---|---|
| 0 | 0 | 12 | | | 0 | 0 | |
| 0 | 250 | 12 | 11.67 | .9 | .25606 | .25606 | 11.669 |
| 250 | 500 | 11.67 | 10.61 | 2.3 | .31674 | .57280 | 10.6109 |
| 500 | 750 | 10.61 | 8.61 | 4.0 | .49911 | 1.0719 | 8.613 |
| 750 | 1000 | 8.61 | 6.489 | 2.0 | .50455 | 1.576 | 6.489 |
| 1000 | 1250 | 6.489 | 5.03 | -3.5 | .30239 | 1.8788 | 5.028 |
| 1250 | 1500 | 5.03 | 3.86 | -5.8 | .2733 | 2.152 | 3.865 |
| 500 | 1750 | 3.86 | 2.98 | -8.0 | .245 | 2.397 | 2.975 |
| 1750 | 2000 | 2.98 | 2.29 | -9.0 | .2406 | 2.638 | 2.285 |
| 2000 | 2250 | 2.29 | 1.8 | -10.2 | .228 | 2.867 | 1.76 |

## Free-Turbine APU

The starting system for the free-turbine APU was assumed to be the same as that for the single-shaft APU with a fluid coupling, and the starting torque characteristics were added to Figure 49.

## Single-Shaft APU, Direct-Drive AGB

The AGB-mounted components included:

1. Generators 1 and 2, rated at 20/30 kva, 12000 rpm;
2. Pump No. 1, rated 3 gpm at 1500 psig, 8000 rpm;
3. Pump No. 2, rated 5 gpm at 1500 psig, 8000 rpm;
4. Lube Pump, rated 1 hp, 8000 rpm.

No electrical output was assumed during the APU starting cycle; it was assumed that the hydraulic pumps pressurized the systems and supplied null flows through three servo valves and pumps; and the lube pump was assumed to supply the regular flow of oil.

### Pump No. 1

The speed at which sufficient flow was developed to satisfy pump needs, 1060 rpm, was calculated considering mechanical and volumetric efficiency losses and servo leakage. Relationships for drag torque were developed for speeds less than and greater than 1060 rpm.

### Pump No. 2

For the 5-gpm pump, 806 rpm was determined to be the speed at which sufficient flow was developed to satisfy pump needs and corresponding drag torque relationships were developed for speeds less than and greater than 806 rpm.

### Lube Pump

A drag-torque relationship was calculated for the lube pump which did not change at any specific value of speed.

### Accessory Gearbox

The friction drag of the gearbox was assumed to be 3 percent of transmitted torque.

### Generators

Based on 1-hp fan drag at 12,000 rpm, a relationship was developed for generator drag torque as a function of speed.

The moments of inertia were calculated for the AGB-mounted components and for the AGB gears. Drag torques and moments of inertia have been listed in Table LII. The correction factor of 2.3 was applied to calculate drag torques at -65°F. These data were plotted in Figure 50.

TABLE LII. INERTIA AND DRAG TORQUE FOR AGB-MOUNTED COMPONENTS

| Component | Moment of Inertia (slug-ft$^2$) | Drag Torque (lb-ft) |
|---|---|---|
| Generator No. 1 | $733 \times 10^{-5}$ | $1.03 \times 10^{-8} N^2$ |
| Generator No. 2 | $733 \times 10^{-5}$ | $1.03 \times 10^{-8} N^2$ |
| Lube Pump | $5.2 \times 10^{-5}$ | $3.381 \times 10^{-5} N^2 + .416$ |
| 3-gpm Pump | $1.12 \times 10^{-5}$ | for $0 < N < 1060$ RPM |
| | | $1.536 \times 10^{-7} N^2 + .34$ |
| | | for $N > 1060$ |
| | | $\frac{1827.7}{N} + .34$ |
| 5-gpm Pump | $3.1 \times 10^{-5}$ | for $0 < N < 806$ RPM |
| | | $4.412 \times 10^{-6} N^2 + .566$ |
| | | for $N > 806$ |
| | | $\frac{2309.9}{N} + .566$ |
| Gearbox | $781. \times 10^{-5}$ | 3% of total output drag |

For hydraulic APU starting, accumulator-motor characteristics:

Total volume = 95.5 in.$^3$

Precharge = 800 psig at 60°F or 607.7 psig at -65°F

Full Charge = 4000 psig at -65°F

Gas volume at -65°F and 4000 psig,

$V_i = 42.26$ in.$^3$

Motor displacement (initial torque = 22 lb-ft, Figure 50)

$$d = .415 \text{ in.}^3/\text{rev}$$

Rated motor power = 33.4 hp (6.8-lb motor)

Moment of inertia, $I = .1069 + .0226 = .1295$ slug-ft$^2$

Calculated torque characteristics and starting times were listed in Table LIII, and the starting torque characteristic was plotted in Figure 50.

TABLE LIII. STARTING TIME FOR SINGLE-SHAFT DIRECT-COUPLED APU

| $N_1$ (rpm) | $N_2$ (rpm) | $\tau_{s1}$ (lb-ft) | $\tau_{s2}$ (lb-ft) | $(\tau_e + AGB)_a$ (lb-ft) | $\Delta t$ (sec) | $\Sigma\Delta t$ (sec) | Check $\tau_{s2}$ (lb-ft) |
|---|---|---|---|---|---|---|---|
| 0 | 0 | 22 | | | | | |
| 0 | 250 | 22 | 21.31 | 11.4 | .3306 | .3306 | 21.309 |
| 250 | 500 | 21.31 | 19.29 | 11.0 | .36455 | .69515 | 19.287 |
| 500 | 750 | 19.29 | 15.79 | 11.0 | .51839 | 1.2135 | 15.794 |
| 750 | 1000 | 15.79 | 10.80 | 9.5 | .89336 | 2.107 | 10.801 |
| 1000 | 1250 | 10.80 | 8.226 | 0 | .356 | 2.463 | 8.226 |
| 1250 | 1500 | 8.226 | 6.295 | -4.2 | .296 | 2.959 | 6.295 |
| 1500 | 1750 | 6.295 | 4.89 | -8.8 | .236 | 2.995 | 4.893 |
| 1750 | 2000 | 4.80 | 3.86 | -13 | .195 | 3.190 | 3.860 |
| 2000 | 2250 | 3.86 | 3.08 | -16 | .174 | 3.364 | 3.079 |

## APPENDIX IV

## APU STARTING SYSTEM ANALYSIS

This analysis applies to starting systems for a single-shaft APU proposed for SPS configuration D. The analysis includes an APU-engine drag torque calculation, and determination of the characteristics of a hydraulic starting system and an electrical starting system. The drag torque and polar moment of inertia of the APU were assumed to be the same as the characteristics used in the previous appendix, which were equivalent to those published data for the gas generator of an 85-hp free-turbine starter engine.

### ENGINE DRAG TORQUE DETERMINATION

APU drag torque characteristics at -25°F were determined from the characteristics at 60°F and -65°F using the equation

$$\frac{\tau}{\mu^n \rho} = \text{constant}$$

or, at sea level,

$$\frac{\tau T}{\mu^n} = \text{constant}$$

where
$\tau$ = torque at starter pad
$T$ = APU-inlet air temperature
$\mu$ = oil viscosity

At 60°F, $\tau$ = 7.73 lb-ft and $\mu$ = 15 centistokes.
At -65°F, $\tau$ = 11.4 lb-ft and $\mu$ = 13,000 centistokes.
By calculation, n = .01679.
At -25°F, $\mu$ = 625 centistokes, and by calculation, $\tau$ = 9.84 lb-ft.
The APU drag torque characteristic developed for -25°F in accordance with the above technique is shown in Figures 51 and 52.

### HYDRAULIC STARTING SYSTEM

The accumulator-motor torque characteristics, developed at -25°F day conditions, were determined as follows:

Motor displacement, d = 0.415 in.$^3$/rev
Accumulator capacity = 95.5 in.$^3$
APU moment of inertia, I = .1295 slug-ft$^2$

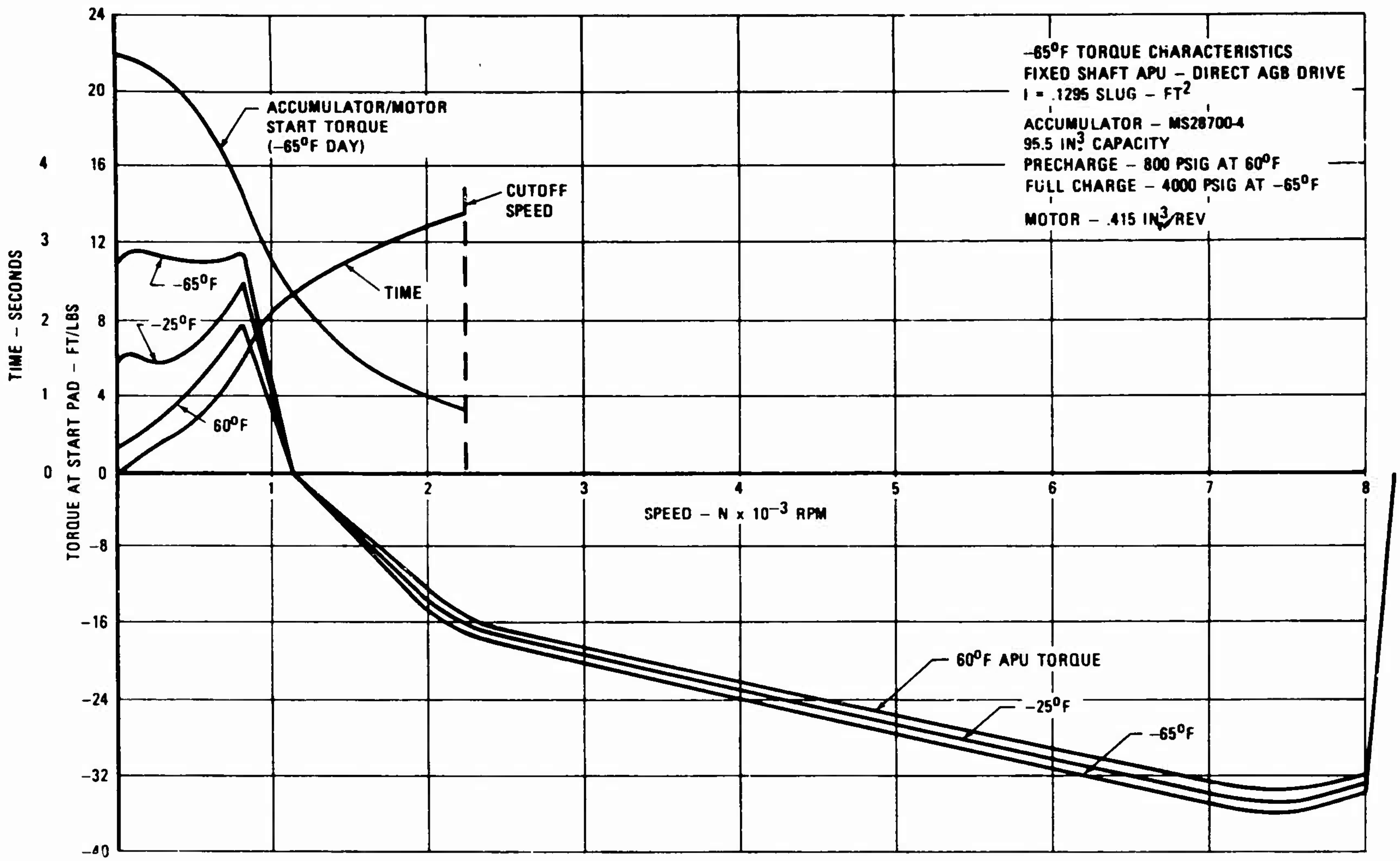



Figure 51. Starting Torque-Speed Characteristics for Single-Shaft APU at -65°F (Hydraulic Starting).

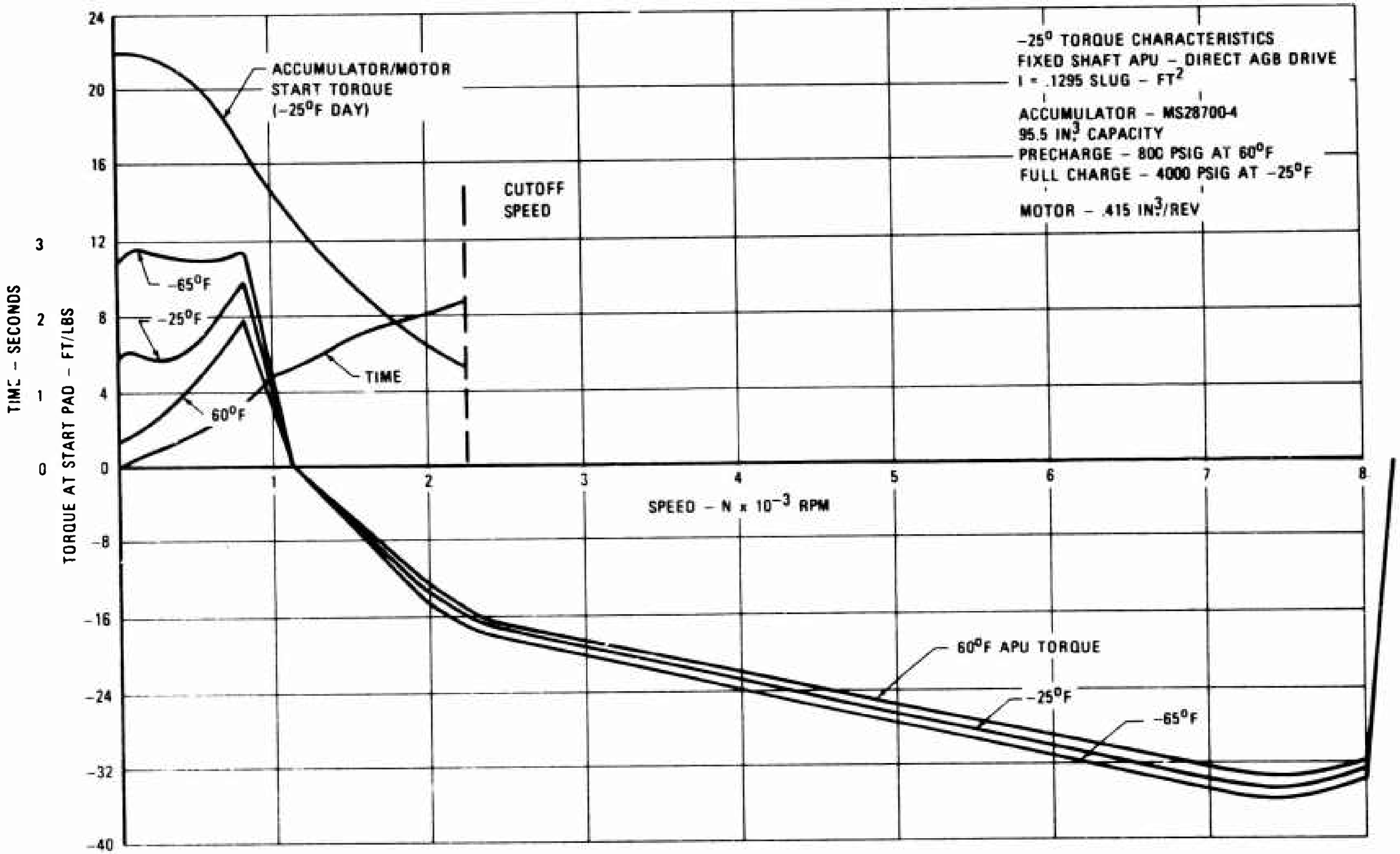



Figure 52. Starting Torque-Speed Characteristics for Single-Shaft APU at -25°F (Hydraulic Starting).

Time increment to accelerate shaft speed $\Delta N$ rpm:

$$\Delta t = \frac{2\pi I \Delta N}{60(\tau s_{av} - \tau e_{av})} \tag{10}$$

where $\tau s_{av}$ = average starter torque during interval N
$\tau e_{av}$ = average APU drag torque during interval N

Starter torque at the end of the interval,

$$\tau s_2 = \frac{P_i d}{24\pi} \left[ \frac{V_i}{\frac{d}{60} N_2 \sum_{o}^{N} \Delta t + V_i} \right]^k \tag{11}$$

where subscript i is for initial conditions. At -25°F and 800 to 4000 psig, average k was 2.55.

Accumulator precharge at 60°F = 800 psig, at -25°F = 669.2 psig.

Gas volume at -25°F and $P_i$ = 4000 psig,

$$V_i = 95.5\left(\frac{669.2}{4000}\right)^{\frac{1}{2.55}} = 47.37 \text{ in.}^3$$

Calculated torque characteristics and starting times are listed in Table LIV.

TABLE LIV. HYDRAULIC APU STARTING TORQUE AND TIME

| $N_1$ (rpm) | $N_2$ (rpm) | $\tau S_1$ (lb-ft) | $\tau S_2$ (lb-ft) | $\tau e_{av}$ (lb-ft) | $\Delta t$ (sec) | $\Sigma\Delta t$ (sec) | Check $\tau S_2$ (lb-ft) |
|---|---|---|---|---|---|---|---|
| 0 | 250 | 22 | 21.56 | 6.2 | | .2176 | 21.56 |
| 250 | 500 | 21.56 | 20.28 | 6.0 | .227 | .4448 | 20.2797 |
| 500 | 750 | 20.28 | 18.05 | 7.6 | .293 | .738 | 18.048 |
| 750 | 1000 | 18.05 | 14.57 | 9.0 | .464 | 1.202 | 14.572 |
| 1000 | 1250 | 14.57 | 11.98 | 1.0 | .276 | 1.478 | 11.972 |
| 1250 | 1500 | 11.98 | 9.8 | -4.5 | .220 | 1.698 | 9.82 |
| 1500 | 1750 | 9.8 | 8.0 | -8.0 | .200 | 1.899 | 8.02 |
| 1750 | 2000 | 8.0 | 6.6 | -12. | .176 | 2.074 | 6.58 |
| 2000 | 2250 | 6.6 | 5.41 | -15. | .161 | 2.236 | 5.407 |

The computed torque characteristics and starting times are shown in Figure 52 for the -25°F temperature condition. Figure 51 shows the starting characteristics of the same system during -65°F operation conditions. These were determined in the same manner as above; k = 2.6 was average at -65°F. The selected hydraulic system characteristics are tabulated in Table LV.

TABLE LV. SELECTED HYDRAULIC APU STARTING SYSTEM CHARACTERISTICS

| Item | Weight (lb) | Cost ($) | Failures/ 1000 Hrs |
|---|---|---|---|
| Accumulator | 10.1 | 40 | .50 |
| Oil | 1.9 | - | - |
| Starter Motor | 6.8 | 905 | .60 |
| Motor/Pump | 3.6 | 295 | .52 |
| Controls | | | |
| Start Valve | 1.2 | 50 | .25 |
| Pressure Switch | .7 | 40 | .17 |
| Electrical | 1.2 | 50 | .10 |
| Piping | 1.5 | 5 | .08 |
| Reservoir | 1.0 | - | .08 |
| TOTAL | 28.0 lb | $1,385 | 2.30/1000 hr |

A system was designed specifically to start the APU during -25°F ambient conditions, utilizing a smaller accumulator but a larger starting motor. This system would have a weight saving of 3.1 lb, but would cost $70 more than the selected system. It was rejected because the operational characteristics would have very little safety margin if the maximum firing speed was shifted slightly. Also, the kit addition for -65°F service would result in a 3 lb and a $100 disadvantage compared with the selected system.

## ELECTRICAL STARTING SYSTEM

Electrical APU starting used an electrical starter-motor and a nickel-cadmium battery, which also served as the aircraft battery. Because of the relatively large loss of battery power output at low temperatures, analyses were made for normal starting at -25°F and for -65°F, where a kit was permitted to support starting.

Figure 53 shows a plot of APU starting torque at -25°F versus speed, on a starter-motor performance grid. Also shown is motor performance to be expected with batteries of different sizes and temperatures. A 22 amp-hour battery would start the APU at -25°F, and the following equipment is required in the starting system (Table LVI):

TABLE LVI. SELECTED ELECTRICAL APU STARTING SYSTEM CHARACTERISTICS

| Item | Weight (lb) | Cost ($) | Failures/ 1000 Hrs |
|---|---|---|---|
| Starter Motor | 10.0 | 800 | .267 |
| 22 Amp-Hr Battery | 55.0 | 450 | .187 |
| Wire | 0.7 | 25 | .168 |
| Controls | | 104 | |
| Starter/Cut-Off Relay | 3.0 | | .00524 |
| Wire | 0.25 | | |
| TOTAL | 68.95 lb | $1,379 | .62724 |

Figure 54 shows a plot of APU starting torque at -65°F versus speed on a starter motor performance grid. Also shown is motor performance to be expected with batteries of different sizes and temperatures. The 22 amp-hour battery at -65°F will not start the APU. All items needed for -25°F start are required to start the APU at -65°F, plut a kit consisting of an insulated box designed to keep the battery temperature from going below -25°F for a 72-hour period, with outside ambient temperature -65°F. The insulated box added 48 lb to the weight and $600 to the cost, and detracted slightly from the reliability of the electrical APU starting system.

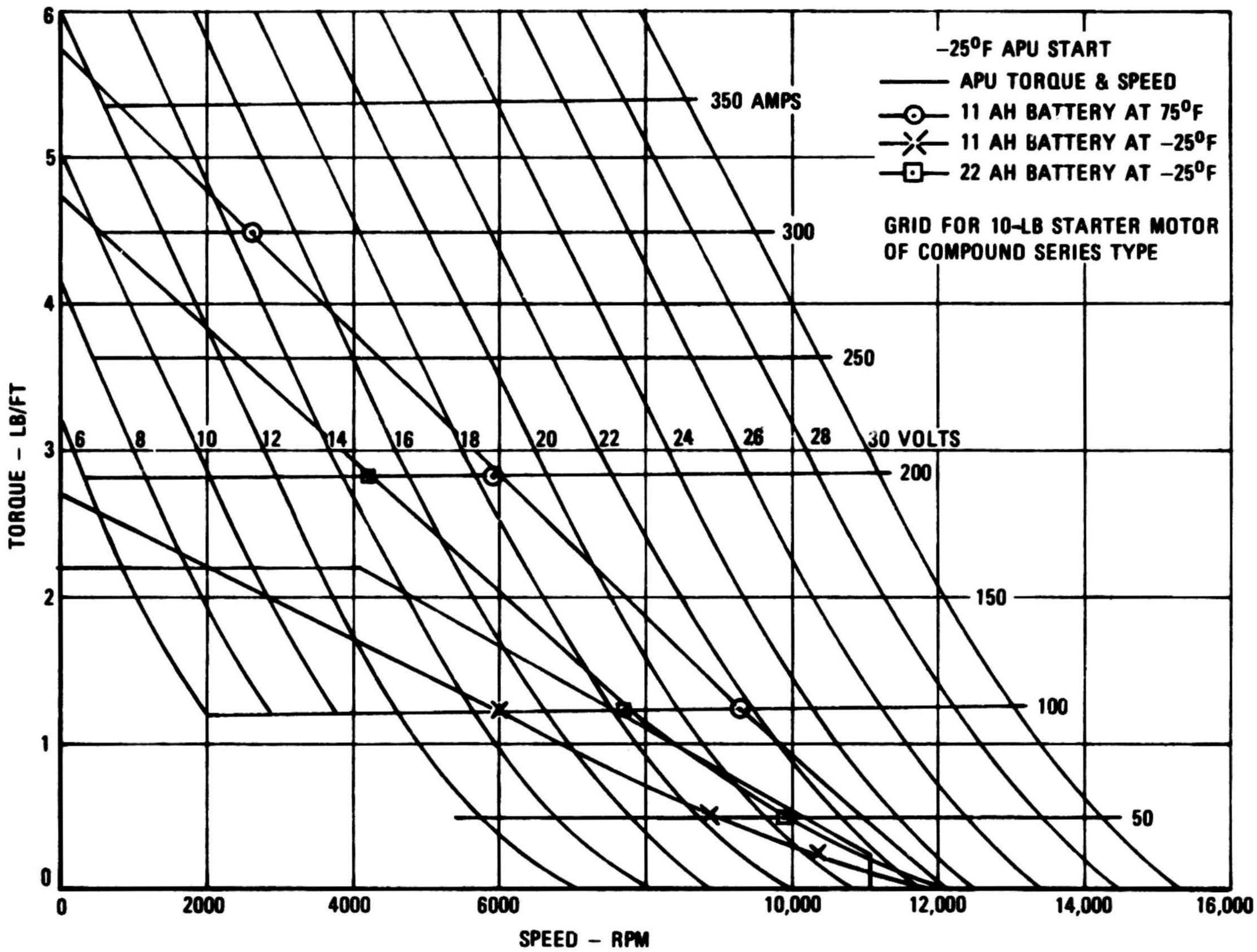



Figure 53. Electric Starter-Motor Torque-Speed Characteristics for Single-Shaft APU Starting at -25°F .

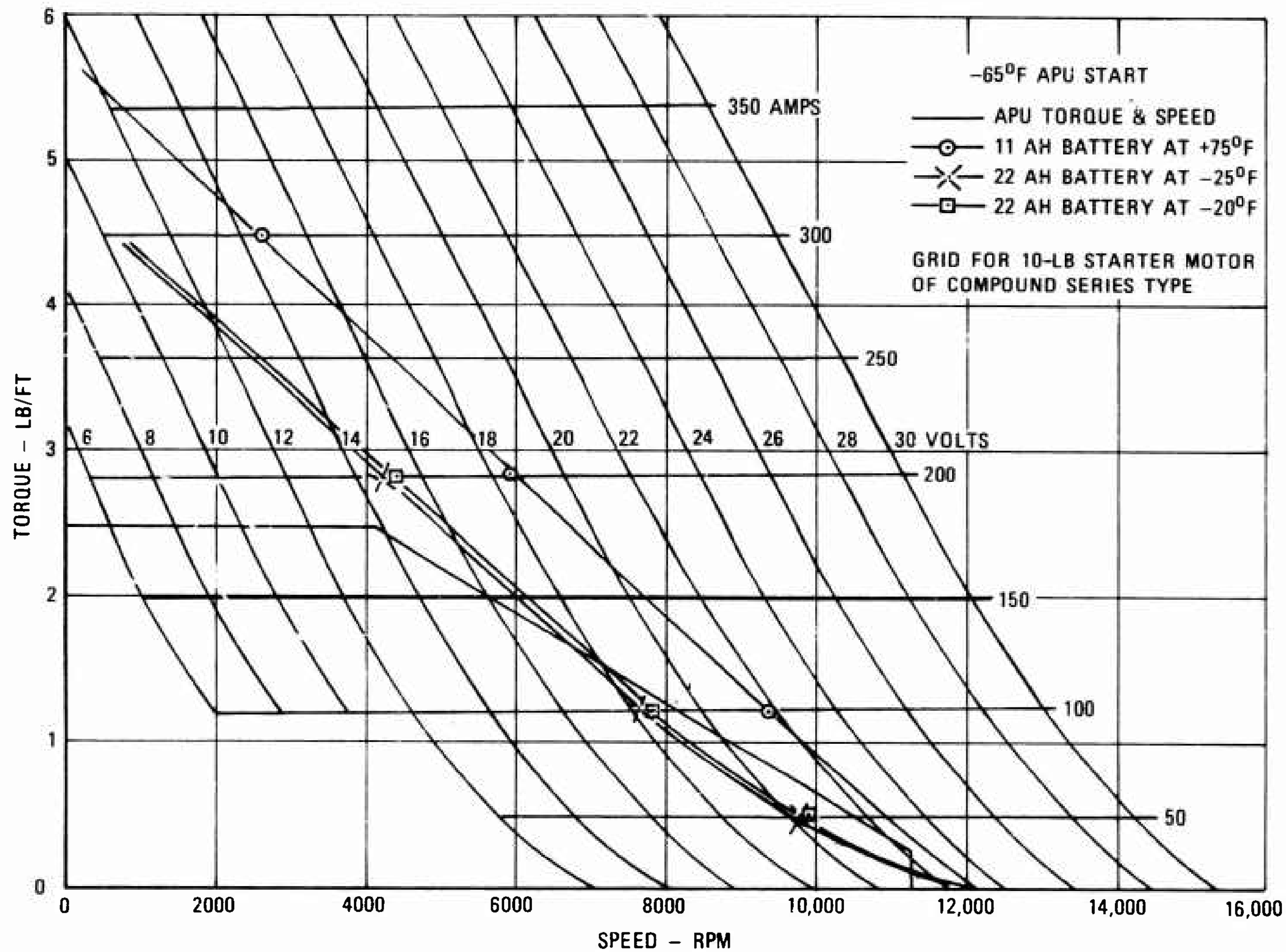



Figure 54. Electric Starter-Motor Torque-Speed Characteristics for Single-Shaft APU Starting at -65°F.